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USER'S GUIDE TO Xgbm: AN X-WINDOWS SYSTEM TO COMPUTE GAUSSIAN BEAM SYNTHETIC SEISMOGRAMS

Version 1.1 - March 31, 1993

J. Peter Davis and Ivan H. Henson

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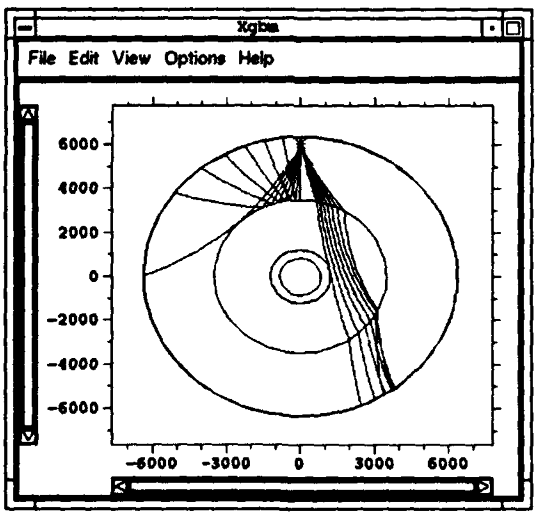
Alexandria, Virginia 22314-1581



under Contract F29601-91-C-DB04

Prepared for:
PHILLIPS LABORATORY
KIRTLAND AFB, NM 87117-5320

Monitored by:
ADVANCED RESEARCH PROJECTS AGENCY
NUCLEAR MONITORING RESEARCH OFFICE
3701 NORTH FAIRFAX DRIVE
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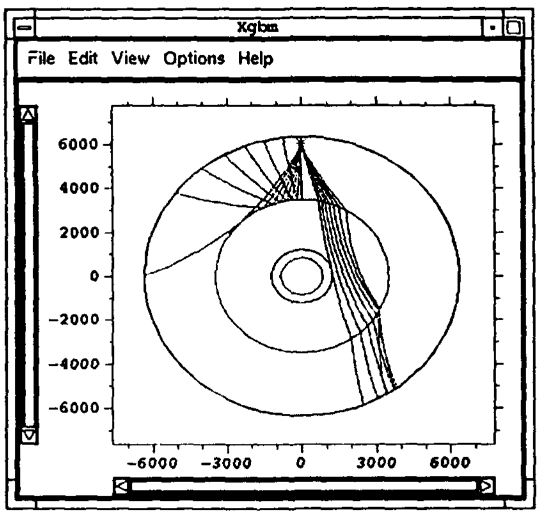

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Table of Contents

0. Contents ... i
1. INTRODUCTION ... 1
2. BACKGROUND ... 2
    2.1 Functional Flow ... 2
    2.2 System Architecture ... 3
3. INSTALLATION ... 4
4. STARTING ... 5
    4.1 IPC ISIS Mode ... 5
    4.2 IPC ipcc Mode ... 6
    4.3 non-IPC Mode ... 7
5. TUTORIAL SESSIONS ... 7
    5.1 Model Manipulation ... 7
        5.1.1 Model input ... 8
        5.1.1.1 Model input -- standard models ... 8
        5.1.1.2 Model input -- user-defined models ... 12
        5.1.2 Model editing ... 13
        5.1.2.1 Moving a knotpoint ... 14
        5.1.2.2 Changing parameters of a single knotpoint or triangle ... 14
        5.1.2.3 Adding knotpoints ... 15
        5.1.2.4 Creating discontinuities and changing sets ... 15
        5.1.3 Model output ... 17
    5.2 Source/Receiver Manipulation ... 17
        5.2.1 Adding/deleting sources ... 17
        5.2.2 Adding/deleting receivers ... 18
        5.2.3 Repositioning sources and receivers ... 18
        5.2.4 Using geotool to positioning source and receivers ... 19
    5.3 Phase Selection ... 19
        5.3.1 Standard phases in list ... 19
        5.3.2 Standard phases not in list ... 21
        5.3.3 Non-standard phases ... 21
    5.4 Seismogram Computation ... 22
    5.5 Color Display ... 26
    5.6 Interfacing with GIS ... 27

6. COMMON ERRORS AND PITFALLS 30
7. BUTTON ACTIONS 30
7.1 FILE Pulldown Menu 30
7.2 EDIT Pulldown Menu 31
7.3 VIEW Pulldown Menu 31
7.4 OPTIONS Pulldown Menu 31
7.5 Xgbm Model Choice popup 32
7.6 User-defined Models popup 32
7.7 Xgbm OutfilePrompt popup 32
7.8 Make Phase popup 32
7.9 Edit Model popup 33
7.10 changeVel popup 33
7.11 Receiver String popup 33
7.12 coordinates popup 33
7.13 Phase List popup 34
7.14 Xgbm Seismogram Computation popup 34
7.15 Travel-Time Curves popup 35
7.16 Input User-Defined Phases popup 35
7.17 Save Selected Phases popup 35
7.18 Kuepper signal 35
7.19 Xgbm Src-Time Funct Input popup 35
7.20 Xgbm Focal Mechanism popup 36
7.21 Seismogram length popup 36
7.22 Xgbm Rayfile Name Input popup 36
7.23 Xgbm Information popup 36
7.24 GIS Input popup 36
8. KNOWN BUGS 36
9. REFERENCES 37
Appendix A. IPC Message Formats A-1
Appendix B. File Formats B-1
Appendix C. Velocity Models C-1
Appendix D. CSS 3.0 Format D-1

1. INTRODUCTION

This manual is to introduce the user to the *Xgbm* program and its associated module *GBseis*. The two programs in tandem are designed to allow the user to create and manipulate intricate, laterally heterogeneous, two dimensional (2-D) velocity models of the Earth's interior and then to compute synthetic seismograms for those models using Gaussian beams. The user is referred to *Weber* (1988a) for an outline of the theory of Gaussian beams as implemented here and a definition of some of the terms used throughout this manual.

Xgbm and *GBseis* may be run either in conjunction with the *ISIS* interprocess communication (IPC) software available at the Center for Seismic Studies (CSS), a second IPC module distributed with the *Xgbm* package, or as stand-alone programs. If either of the IPC software packages is utilized, interaction with the *geotool* data analysis program is possible, provided one is using *geotool* version v1.2 or higher. The software has recently been modified to interface with the Geographic Information System (GIS) at CSS.

The code is based on Fortran programs originally written by Michael Weber of the Seismologisches Zentralobservatorium Gräfenberg, Erlangen, Germany. Under contract F29601-91-C-DB04 from Phillips Laboratory and monitored by DARPA, Principal Investigators Peter Davis and Ivan Henson translated the original Fortran into C and constructed around it a graphics shell of C and Motif©-based X-Windows widgets, so that what earlier required user editing of large data files could now be accomplished with graphics tools. This distribution was compiled on a Sun 4/360S running OS 4.1.3 and X11 Release 5. Groups at the Ruhr University, Southern Methodist University, the Oklahoma Geological Survey, and the GFZ Potsdam report they have successfully executed version 1.0.2 of these programs at their installations. In several instances, the code has run successfully under OpenWindows as well, but this required minor modifications to the binaries because of the non-standard location of X resource files specified at compilation.

A number of tests of the system's accuracy in both traveltime calculation and waveform synthesis have been conducted. The results of these checks are described in *Davis and Henson,* (1993). Generally speaking, the new code is as accurate as the original Fortran, which was itself carefully checked against reflectivity and finite difference codes.

The next section contains a brief outline of the underlying concepts of the system. There follow several sections explaining how to initiate the programs, some example tutorial sessions describing how to accomplish common tasks, and a detailed description of the action of each button and display in the graphics module *Xgbm*. Because it has not been possible to eliminate all shortcomings, a section is included in which known bugs are described. For those who wish to read journal articles relating research in which the original Weber code was used, references are listed at the end. So that developers might exploit the modular design of the system, two appendices have been added in which the format of IPC messages and of input/output files are detailed.

Questions and comments may be directed to the authors (davis@seismo.CSS.GOV and ihenson@seismo.CSS.GOV). The authors will respond as time and resources permit.

Bug reports will be posted within the same ftp directory on seismo.CSS.GOV from which this package is available.

2. BACKGROUND

2.1 Functional Flow

The functional flow for computing Gaussian beam seismograms and/or calculating traveltimes through heterogeneous media is simple:

(1) model input or creation,
(2) source-receiver geometry and component phase specification,
(3) dynamic raytracing,
(4) traveltime and /or seismogram computation, and
(5) display of results.

Step one is to use *Xgbm* either to create an input model from scratch or to access a fully two-dimensional model which has been created previously. The former is generally done by beginning with a one-dimensional (1-D) model and extending it into a second dimension. Once in this extended form the user may impose large-scale heterogeneity, such as a subduction zone in the case of a global model, or a localized heterogeneity, such as a sedimentary basin with low-velocity lens in the case of a regional model. Additional heterogeneity may be created by manipulating the model elements manually with a mouse. Whether created *ab initio* or read in and modified, the model may be stored for future use at the end of this step.

The velocity model is specified as a series of knotpoints and triangles. Each knotpoint fixes v_p, v_s, and ρ at a point in space. Because the velocity gradient is assumed to be linear between each knotpoint, the velocity is effectively specified fully in two dimensions. (One exception is at discontinuities: there two knotpoints are spatially co-located and specify the velocity and density on each side of the discontinuity.) Knotpoints are grouped into triplets to form triangles. A value for Q_α and Q_β, the P- and S-wave attenuation, is assigned to the space enclosed by each triangle. *Xgbm* tracks which triangles share knotpoints and are therefore "neighbors."

Under these linear gradient conditions, there is an analytical solution for the raypath across a triangle. Once the position of the source has been specified and the phases to be traced have been chosen (step two), raytracing through the model (step three) is accomplished by tracing stepwise analytically through each component triangle along the raypath. Anelasticity is accounted for by computing a t^* operator using Q_α and Q_β from the triangles. Results from this step are also stored for later use by *GBseis*. Note that receiver position information is not essential at this point and is not written out with the other raytracing information. The user usually finds it convenient, however, to input this information at the same time the source is positioned.

The essentials for step four, traveltime calculation or seismogram computation, are now complete. In the Gaussian beam method, it is not necessary to compute rays which travel directly from source to receiver. Rather, it is sufficient to compute a number of rays which originate at the source and terminate within several wavelengths of the receiver. It is possible to generate a traveltime curve without specifying the receiver position. However, to obtain a seismogram, one must first specify precisely the position of the receiver relative to the source. The seismogram consists of a weighted sum of rays which terminate within the required wavelength limit of the receiver. Traveltimes for distances not corresponding to a ray endpoint are found by using slowness to extrapolate the traveltime of the nearest terminating ray.

The computed synthetic seismograms are written out in CSS 3.0 schema format. Step five, the display of results, is not possible with the software modules provided in this package. Programs to display CSS format data or to translate it into other formats may be obtained by contacting the CSS staff.

One aspect about the velocity model presentation needs to be clarified. *Xgbm* is capable of displaying a model in two modes, flattened and spherical. The default mode, flattened, shows the model after its coordinates, velocities and densities have been passed through a transformation governed by the *earth flattening approximation* (EFA). The particular transformation in use here is the one suggested by *Müller* (1977). There is a limit near the Earth's center where this EFA is no longer valid. A lower bound on depth corresponding to this breakdown point has been installed in the program. The user will discover that any attempt to set the depth lower than the EFA breakdown point (about 800 km from the center) will fail.

Use of the EFA is evident in a second way. When the user looks at, or edits, the text widget showing the source depth, that value is always expressed in unflattened coordinates, no matter what the display is. If the display is currently flattened, it will be apparent that the source position in the display will be different than that indicated in the text widget. The two values are related by

$$z' = R \ln \frac{R}{R - z}$$

where z and z' are the unflattened and flattened depths, respectively, and R is the earth's radius.

The newest and potentially most useful feature of *Xgbm* is the program's ability to make use of surface topography and depth-to-moho information contained in geographic databases and available through raster server programs such as described by *Fielding et al.* (1992). The module *gc_raster* acts as an interface with raster server programs in other systems and formats the output for use by *Xgbm*. Details of how this works are provided in Section 5.6.

2.2 System Architecture

This brief subsection describes how the above tasks are divided between the modules *Xgbm* and *GBseis*. Both are designed to run either by exchanging interprocess communication messages (IPC mode) or through flat files (non-IPC mode). See Section 4 to learn how to initiate the system in the two different modes. The details of IPC message format are elaborated in Appendix A. The contents of all files are explained in Appendix B.

Xgbm handles all velocity model manipulation and acts as the hub of all IPC communication. Source-receiver geometry may be set either by *Xgbm* graphics (non-IPC) or by IPC messages received by *Xgbm*. In limited cases, phases to be traced are selected via IPC messages as well, but in general, the user should select the phases using *Xgbm* lists. All raytracing is performed by *Xgbm*. Once the raytracing results are written to an output file, seismograms and/or traveltimes may be obtained in either mode from *GBseis*. For convenience, *Xgbm* may be used to specify the source-time function and source type, but this is not necessary.

3. INSTALLATION

Version 1.1 of *Xgbm* and *GBseis* are distributed as a compressed tar file tar.Xgbm.v1.1.Z. This should be moved to the directory where one wishes these programs to reside and where they will be accessible to everyone who wishes to use them. In this example, that directory will be called "/voodoo". The UNIX command to move the file is

```
mv tar.Xgbm.v1.1.Z /voodoo
```

Now move to /voodoo and uncompress the file:

```
cd /voodoo; uncompress tar.Xgbm.v1.1
```

Finally unpack the tar file:

```
tar xvf tar.Xgbm.v1.1
```

There should now be two directories, one named bin and one named vmodels. The former contains the executable binaries *Xgbm* and *GBseis* that perform velocity model manipulation and compute synthetic seismograms, and in addition, a binary called *ipcc* used for interprocess communication. The X resources for the graphics module *Xgbm* are found in the X11 subdirectory of bin. The directory vmodels contains ASCII files of velocity models in a format capable of being read by *Xgbm*. Please do not edit them, but do feel free to copy them as examples of files in a format *Xgbm* can input. The binaries have been compiled on a Sun SPARC running SunOS Release 4.1.3. You will also require X-Windows, but no dynamic libraries.

The files should now be positioned correctly in your system. Please add the bin directory to your path. This is best done by editing your .cshrc file, but may be accomplished temporarily by typing:

```
set path = ($path /voodoo/bin)
```

Finally, edit the file /voodoo/bin/X11/XgbmMain. Everywhere the directory path */usr1/contracts/1600/src/X11/* appears, please substitute */voodoo/bin/X11/*. The installation should now be complete. See the next section for how to start the programs.

While the above simple recipe should work, a more satisfying installation is to move the X resource files from the /voodoo/bin/X11 directory to your system's app-defaults directory, commonly found in /usr/lib/X11. In this case, everywhere */usr1/contracts/1600/src/X11/* appears, the string */usr/lib/X11/app-defaults/* should be substituted. However, if you are using OpenWindows, the directory to which the resources should be moved is not /usr/lib/X11/app-defaults but more likely /usr/openwin/lib/X11. Consult your system documentation and OpenWindows installation notes for which directory to place your resource files.

4. STARTING

The program may be run in any two of three different modes: IPC mode using *ISIS*, IPC mode using *ipcc*, and non-IPC mode. Which of the two IPC modes your version can run is determined at compilation. A given binary will run IPC ISIS mode and non-IPC mode **or** *ipcc* IPC mode and non-IPC mode. This section explains how to start the program in each different mode. Regardless of which mode one chooses, the following environment variables should be set:

name	*default*
XENVIRONMENT	./bin/X11/XgbmMain
GBMODENV	./vmodels
GBWORKENV	.

The default values will be correct only if you are in directory /voodoo where /voodoo follows the example of the preceding section. The package should work independent of home directory if the variables are reset to:

setenv XENVIRONMENT /voodoo/bin/X11/XgbmMain
setenv GBMODENV /voodoo/vmodels

The variable GBWORKENV sets directory to which the output files will be written. If one wishes to place the files in a directory other than the one from which the program was started, say /fondue, then type:

setenv GBWORKENV /fondue

and the files will be written to /fondue.

The environment XENVIRONMENT need not be set if the *Xgbm* resource files in the X11 subdirectory of the distribution have been moved to your system's app-defaults directory during installation. One may then personalize one's *Xgbm* display by recopying selective resources from these files into the user's .Xresources file, editing them, and loading these into the window manager's resource database *xrdb*.

4.1 IPC ISIS Mode

This is the most appropriate mode for working in the software environment which exists at CSS. If you do not have the *ISIS* package and wish to obtain it, please contact the CSS staff. Some familiarity with *ISIS* is assumed here, namely that the user has set the environment variables ISISPORT and AESIRHOST correctly. One must first start an agent, say foo, by typing:

CommAgent -a foo &

It should connect promptly. Now start *GBseis* with the same agent name, GBseis -a foo &

and *geotool* as well, if one desires that display capability:

geotool -a foo &

Finally, start *Xgbm*:

Xgbm -a foo &

A small window should appear, by default, in the upper left hand corner of your screen. You should resize it to the size with which you feel most comfortable. The *-a* flag used when starting *Xgbm* and *GBseis* forces the two programs to run in an IPC mode under group foo.

4.2 IPC ipcc Mode

This mode provides the ease of IPC communication without the overhead involved in the full *ISIS* package. One should first set two environment variables, IPCC_PORT and IPCC_HOST. The simplest case, which should suffice for a single workstation, is:

setenv IPCC_HOST 'hostname'
setenv IPCC_PORT 2001

Now start *ipcc*,

ipcc &

and then *GBseis* and *geotool* if one wishes the latter for display:

GBseis -a &
geotool -a &

Finally, start *Xgbm*:

Xgbm -a &

A small window should appear, by default, in the upper left hand corner of your screen. You should resize it to the size with which you feel most comfortable. The -a flag used when starting *Xgbm* and *GBseis* triggers the two programs to run in an IPC mode. This sequence should suffice for most cases.

There are other possible starting modes, however. In the above example, it was assumed for convenience that the group name would be the user name. If for some reason, another group name was to be used, say foo, start each with a "-a foo" commandline argument:

GBseis -a foo &
Xgbm -a foo &
geotool -a foo &

Also, it is only necessary to have one instance of *ipcc* running on the network. Two or more instances may run as long as they do not share the same port, as set through the IPCC_PORT environment or in the command line:

ipcc port=*port_number*

If a single instance of *ipcc* is running but not on your workstation, connect to it by setting the IPCC_HOST environment to the name of the workstation on which it is running.

4.3 non-IPC Mode

This mode is retained here for historical reasons and has been subsumed in functionality by the ipcc IPC mode. It is the simplest mode of operation, however, and many users will find it sufficient for their purposes. In this case, *GBseis* is not run in background continuously as in the previous two modes. Rather, at each instance *Xgbm* requires that a synthetic seismogram be calculated, *Xgbm* writes an input file (default = .GBinput) for *GBseis* to read and then spawns *GBseis* with a system call. This instance of *GBseis* is initiated with a special flag that tells *GBseis* to obtain the necessary information from the input file, calculate the seismogram and then exit. To start *Xgbm* in non-IPC mode, type:

```
Xgbm &
```

and a small window should appear, by default, in the upper left hand corner of your screen. You should resize it to the size with which you feel most comfortable. The absence of the -a flag used when starting *Xgbm* triggers *Xgbm* to run in a non-IPC mode.

5. TUTORIAL SESSIONS

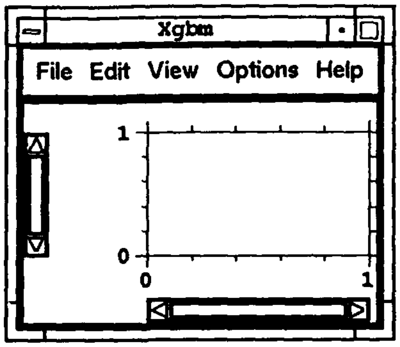
This section is intend to lead the user through a number of common tasks. The order in which they are presented, which follows from the discussion in Section 2, often need not be adhered to rigidly. One may read in a model, trace rays, reposition the source, compute a seismogram, change the model or source position and then iterate on the above, all without difficulty. Some sense of direction is useful however. It is absurd to consider tracing rays before one reads in a velocity model. A more subtle (but critical) point is to remember to write out the raytracing results before attempting to compute a seismogram based upon that raytracing.

The user is assumed to be familiar with X-Windows and how to operate its common widgets: push buttons, toggle buttons, sliders, and lists. Assuming that the button bindings have not been altered in any way, selection is usually accomplished with single click of the left mouse button. By convention, *Ctrl-left* refers to the action of simultaneously depressing the Control key and clicking the left mouse button, *Ctrl-middle*, to simultaneously depressing Control and clicking the middle mouse button, *etc*.

This section does not illustrate all the package's capabilities. The reader is urged to browse through Section 7 after becoming familiar with the basic operation.

5.1 Model Manipulation

The principal design goal of this project was to create a graphics tool to allow the user to construct quickly and easily, complicated 2-D models of seismic velocity. Hence these capabilities of *Xgbm* go to the heart of the software package. The first window presented to the user looks like this:

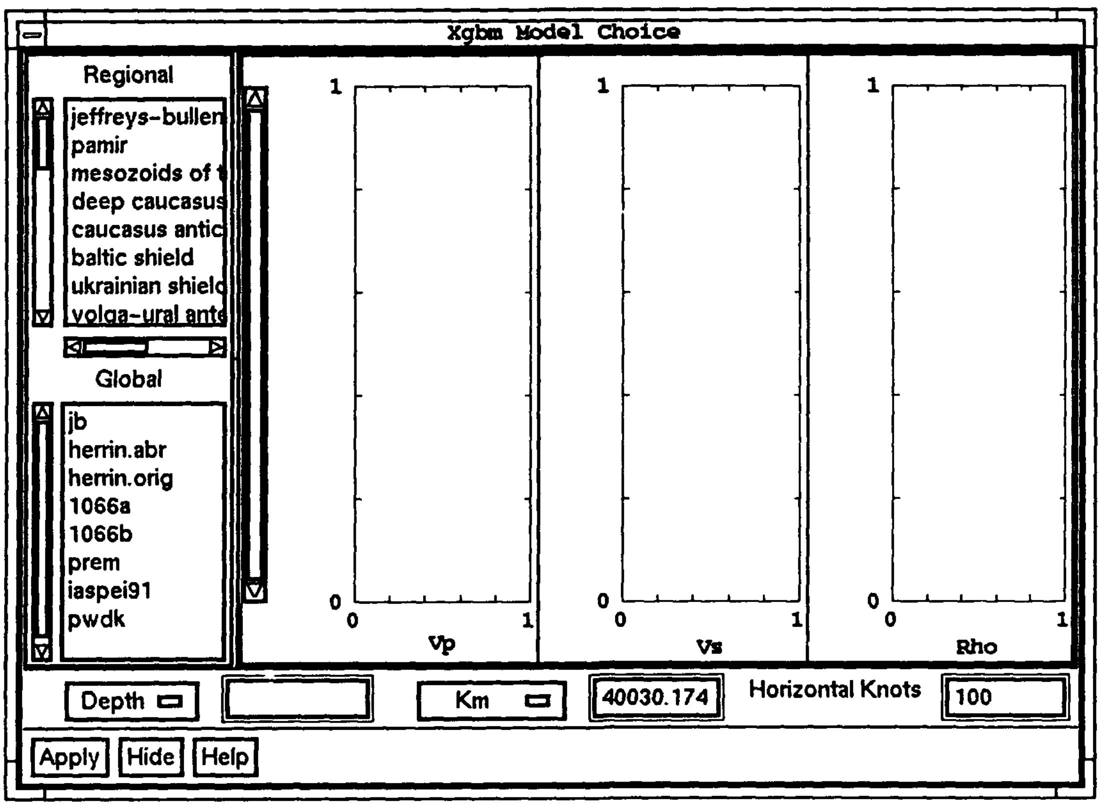


5.1.1 Model input

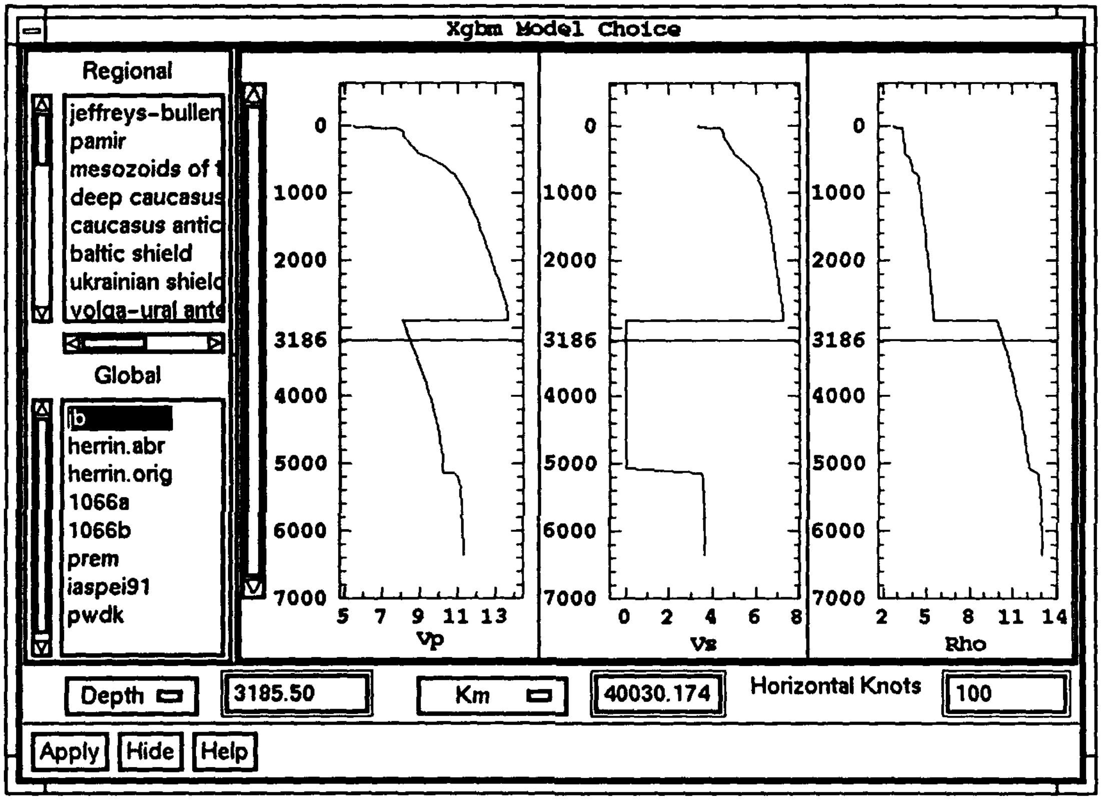
Select the FILE button from the Main menu bar. A pulldown should appear containing the buttons INPUT, SAVE, WRITE, and QUIT. Select INPUT. A further pulldown should appear containing buttons STANDARD and USER-DEFINED. As their names imply, STANDARD is used to read in standard models distributed with the software. USER-DEFINED is used to read in models created by the user in previous work sessions.

5.1.1.1 Model input -- standard models

Select STANDARD. A popup like this should appear:



On the left-hand side are two lists entitled "Regional" and "Global." The regional models are two layer crusts over a half-space. The global models are, in general, models either published as such or derived from traveltime tables. See Appendix C for details. The abr and orig following herrin refer to abridged (smoothed over depths where the velocity gradient was small) and original, respectively. For now, select *jb*. The plots of v_p, v_s and ρ as a function of depth should appear:



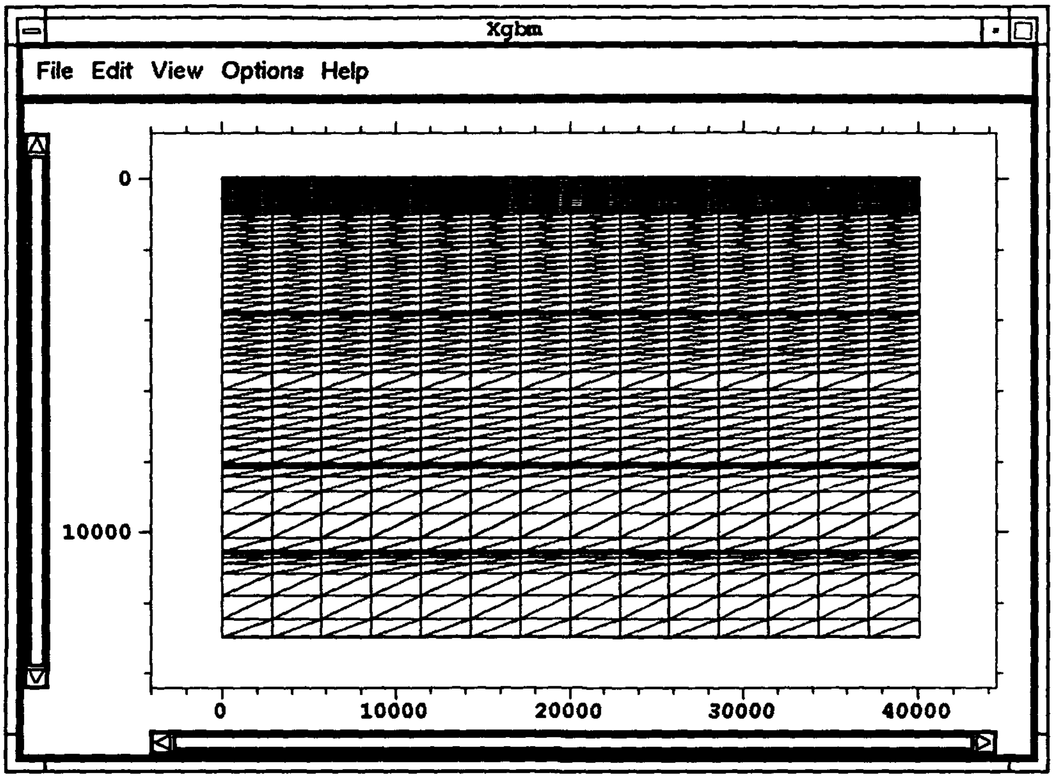
To create a 2-D model, it is necessary to specify the depth (the maximum depth to which model extends), breadth (horizontal distance model extends), and resolution (how widely spaced the knotpoints are). One controls the lower depth bound on the model in one of two ways. The first is by moving the horizontal line segment which appears in all three of the velocity/density plots. If you have selected *jb*, it should appear near the halfway point of the model at 3186 km. You can alter this bottom depth by moving the pointer into the display (either the velocity plots, density plot or the space between them), depressing and holding down the left mouse button, and moving the mouse up and down the screen. The depth at which you release the mouse will be the lower model bound. The second way to control the bound is through the text widget labeled *Depth* in the lower left-hand corner. As one slides the horizontal bar up and down, the value in this text widget is updated. One can edit the text widget to change the depth. Move the pointer into the depth text widget (the rectangle to the right of the *Depth* label) now and double click on the left mouse button. The widget should display in reverse video. If you now hit the *delete* key, the entry should become blank. Type in a new value for the lower bound, say 6200. [If you prefer to work in radius rather than depth, this is also possible. Move the cursor to the label *Depth* and depress and hold the left mouse button. A pull-down will appear containing *Depth* and *Radius*. Slide the pointer onto the word *Radius* and then release the left mouse button. The displays will revise themselves to be functions of radius. You can toggle back and forth, the model lower limit will be the same.] Depending upon the resolution of your display, the depth value displayed to the left of the movable horizontal bar may not agree precisely with the value of the depth text widget because of round-off. The program always set the lower depth bound on the basis of the text widget's value.

You now must set the breadth, which is done with the widget labeled *Km* in the bottom middle of the popup. This text widget should have the peculiar value of 40030.174, the number of km for the circumference of an earth of radius 6371 km. One sets the lateral extent of the model by editing this value in the same fashion as one edited the *Depth* text widget. When working with teleseimic body phases, it is perhaps more natural to work in degrees. Like the *Depth/Radius* toggle, *Km* may be toggled between *Km* and *Degrees*. Toggle this button to degrees now. The text widget should update to 360.00, the number of degrees in circumference. Leave the value at 360 for the time being.

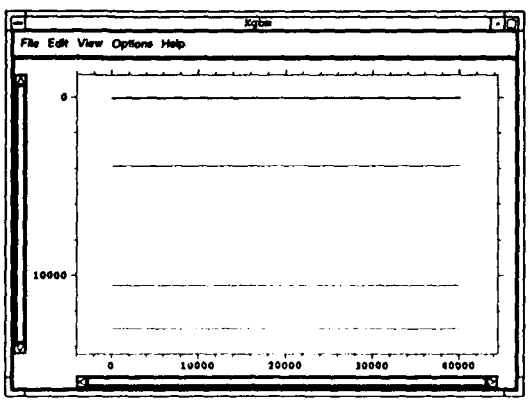
Finally, it is necessary to set the resolution with the *Horizontal Knots* widget in the lower right-hand side. This is done by editing the value in the rectangle to the right of the label. The number 100 there now reflects the number of horizontal knots in the grid which will form the 2-D model. (This will become more apparent in a moment.) Generally speaking, the larger the number of knots, the finer the resolution, but the longer the program execution. The number of vertical knots is not controllable from this popup, but is instead set by the depth points at which one specifies the model parameters. The raw 1-D files from which the plots in this popup are created are contained in files in the */vmodels* subdirectory. Please do not edit or rename these files -- proper execution depends upon them remaining where they are as they are.

Clearly the larger the number of horizontal knotpoints, the shorter the horizontal triangle sides. Again in general one should not have a horizontal side which exceeds the shortest vertical triangle side by a factor of 200 or greater. Examination of the data file */vmodels/GB.jb* indicates that the shortest vertical segment for the jb model is 15 km. Therefore the shortest horizontal segment should be 300 km (2.7°), so for a jb model of breadth 360°, the minimum number of knots required is 134. In order to illustrate some of *Xgbm*'s behavior, violate this constraint by entering the number 15.

The model is now ready. Press the *Apply* button in the lower left-hand corner. (Had you changed your mind at any point, you could have pressed *Hide* instead and the popup would have disappeared.) When you press *Apply*, two things will happen. First the "Xgbm Model Choice" popup will disappear and second, the space below the main menu bar which had been blank before is filled with a grid of triangles. You may need to resize the window to see a display like this:

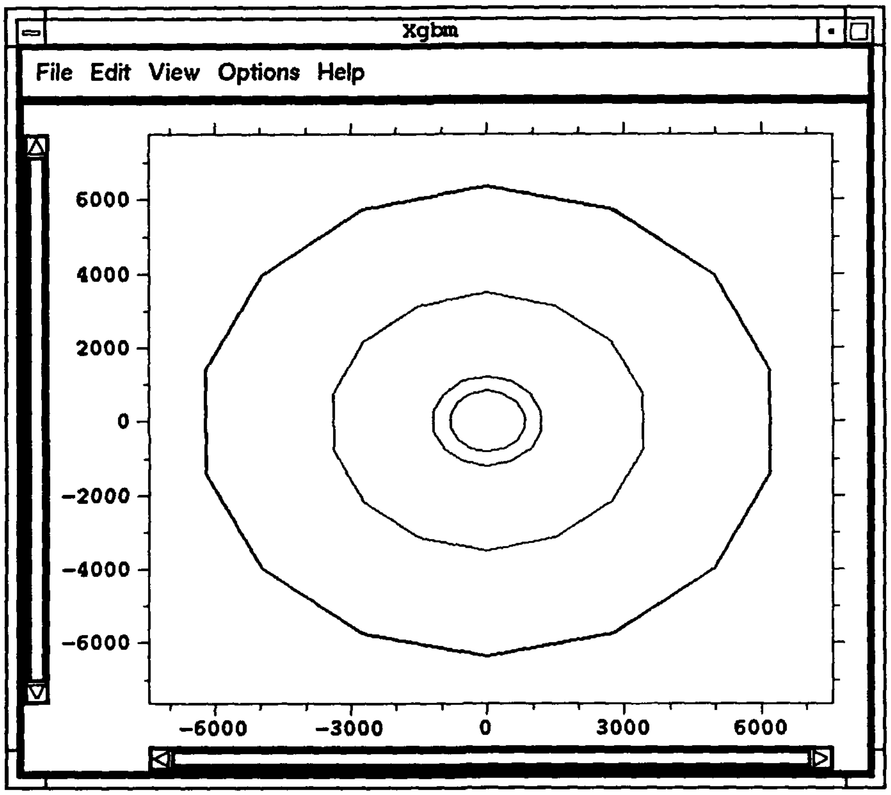


The horizontal scale extends to just beyond 40,000 km, the vertical scale, to just below 12,000 km. This is the jb model in the default "earth flattened" display showing all constituent triangles. The lower limit of 6200 km has been transformed to a value greater than 12,000, but because 6200 is closer than 800 km from the center, the actual lower limit is set to the transformed value of (6371-800). See the note about the EFA in Section 2.1 above. Ordinary triangle sides are shown in black, sides where the velocity increases discontinuously, in red. Exactly where the discontinuities are becomes more apparent when one toggles off the triangle display. To do this, press the VIEW button in the main menu bar, and when the pulldown appears, click on the TRIANGLES toggle button. The display should change -- the triangles will disappear



leaving only four horizontal red lines and two horizontal violet lines (the top and bottom lines). The violet lines represent model boundaries, the red lines, discontinuities at the inner core-outer core boundary, the core-mantle boundary, the Moho, and the Conrad. Had you had set the breadth of your model to be anything less than 360°, there would also be two vertical violet lines marking bounds to the left and right of your model. It would then be impossible to model phases that travel distances greater than 360°.

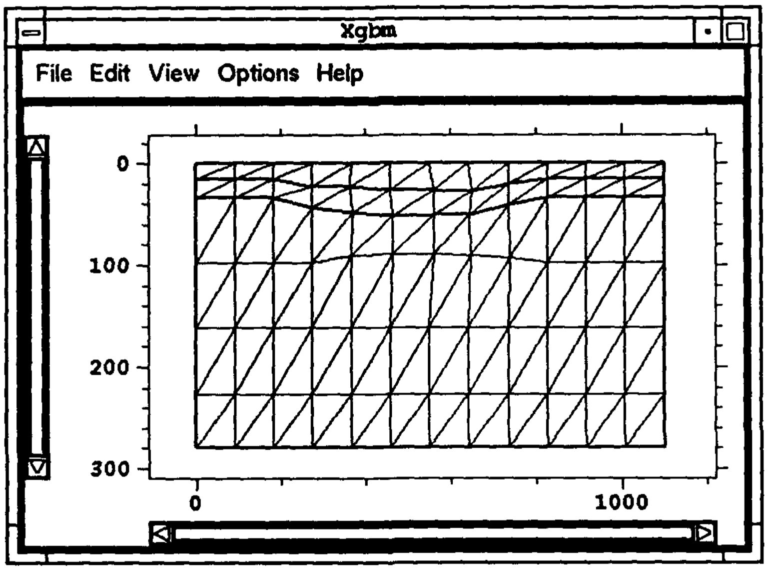
To make this more apparent, change the form of the display by selecting VIEW again but click this time on FLATTEN. The display will revise to



show a series of concentric 15-sided polygons which approximate circles. All calculations are done in the flattened model however. Later in this tutorial, when phases are plotted for this 15 sided earth, it will be apparent that the rays do not terminate along the triangle sides. The traveltimes are nevertheless accurate!

5.1.1.2 Model input -- user-defined models

Select USER-DEFINED. A file selection box entitled "User-defined Models" will appear. Any file in your current working directory ending in ".gb" should appear in the list on the right. By convention, user-defined models end in this suffix. Edit the filter text widget at the top to indicate the path where you have installed the */vmodels* subdirectory. In the installation example, this was */voodoo/vmodels*, so the entry should be changed to */voodoo/vmodels/*.gb*. Then click on the FILTER button at the bottom. The list at the right should include the filename *tutorial.gb*. Select it by either (1) double-clicking the left mouse button on the name, or (2) single clicking the left mouse button (it will change to reverse video) and selecting the OK button at the bottom. In either case, the popup will disappear and the display will indicate an irregular grid of triangles depicting a syncline in the center with slight bowing up of layers in the



mantle beneath it. Had you selected the CANCEL button instead of OK, the popup would simply have disappeared and no new model been read in. Please read Section 5.1.1.1 and note the changes in the display possible through the FLATTEN and TRIANGLES buttons.

For this example, *tutorial.gb* is a 2-D model created in an earlier session of *Xgbm*. If the user-defined model one wished to input had been a 1-D model in ASCII format, the Xgbm Model Choice would have appeared in response to selecting the OK button. The depth, breadth, and resolution of the 2-D extension of the 1-D model are then set as described in Section 5.1.1.1. In this instance, the Regional and Global model lists are rendered insensitive to ensure that only the user-defined model parameters will be set.

5.1.2 Model editing

A velocity model may be changed either by repositioning the knotpoints in space and thereby altering the velocity gradient between knotpoints or by altering the velocity and density at a knotpoint. Resolution may be increased in key areas by adding knotpoints. The velocity model will not change however until the velocity is changed at the new knotpoints or they are moved. That is, the velocity and density at an added knotpoint is computed from that knotpoint's neighbors.

In order to do any model editing and for the MOVE KNOTS and ADD KNOTS buttons to be sensitive, the TRIANGLE toggle button in the VIEW pulldown must be on *i.e.*, the triangles must be visible. (While this is not strictly true, you can try it the other way and observe the peculiar behavior of the display, it is best for visual management of the changes.) In order to have a common display as a starting point, please read in the tutorial.gb model as in Section 5.1.1.2. The model should be in flattened mode and with the triangles visible.

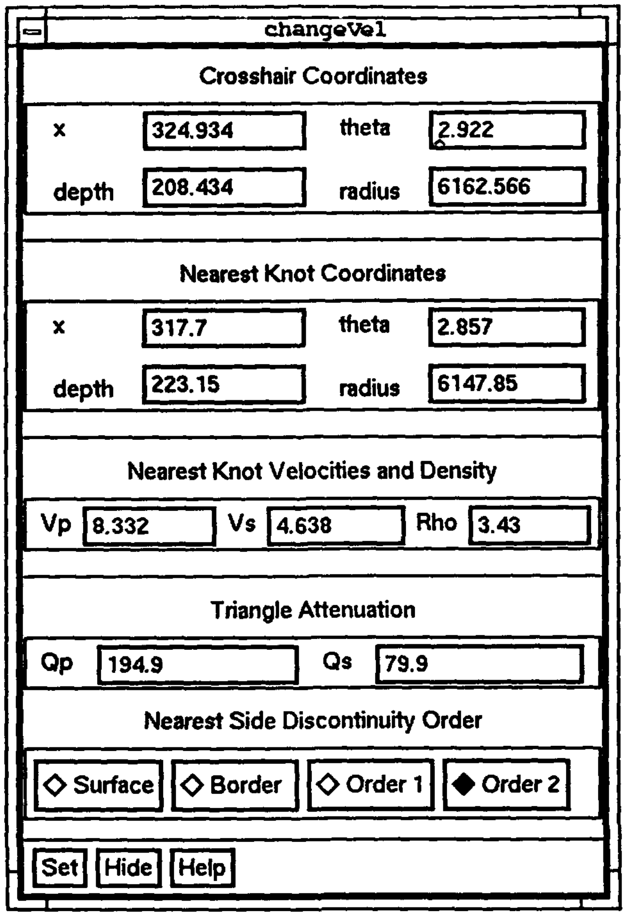
One other function that is generally useful is the capability to zoom in the display on a part of the model that is of interest. Place the pointer at the border of the area on which you wish to zoom. Depress and hold down the middle mouse button, dragging the pointer across the area of interest. As long as you hold down the mouse button, a rectangle will be displayed with one corner at the starting point and the corner diagonally opposite at the current pointer position. Drag the mouse so that the rectangle encloses the area of interest, and then release the middle mouse button. The display should zoom. To return to the previous display, be certain the pointer is still in the window, and click the middle mouse button once.

5.1.2.1 Moving a knotpoint

Select the EDIT pulldown in the main menu bar. Toggle the MOVE KNOTS toggle button from that pulldown to the *'on'* position. It should appear highlighted if *'on'*. Position the pointer near a knotpoint that is on the interior of the model. Points on the boundary other than the surface cannot be moved in this version of *Xgbm*. Perform a *Ctrl-left drag*. The knotpoint should move as you drag the mouse, and the triangles sides attached to that knotpoint should turn red as the point is dragged. There is a limit to how far the knotpoint may be dragged, since triangle sides may not cross. If one tries to drag the knotpoint too far, the knotpoint simply ceases to move. This may be repeated indefinitely. When the MOVE KNOTS toggle is turned off, then it becomes again impossible to move the knotpoints.

5.1.2.2 Changing parameters of a single knotpoint or triangle

Move the pointer into the window in which the model is displayed and strike the *'c'* key. A set of crosshairs should appear in the window. Position the crosshairs close to the knotpoint whose velocity or density you wish to change by holding down the left mouse button and dragging it across the model display. Release the mouse button when the crosshairs are aligned with your target. Select the PARAMETERS button of the EDIT pulldown. A popup entitled "changeVel" should appear:



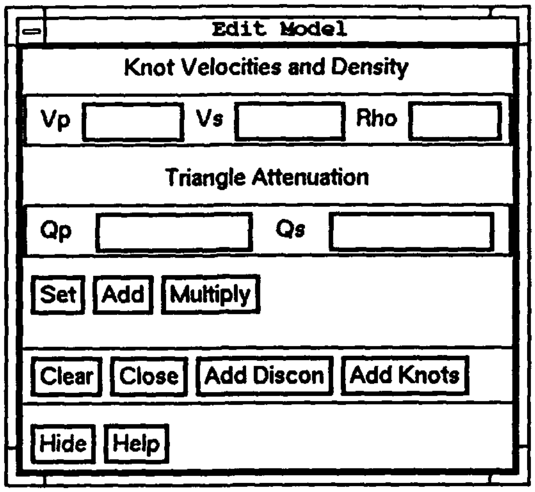
As you reposition the crosshairs about the screen, the text widgets in the popup will be updated accordingly. To alter the properties of the nearest knotpoint or the attenuation values of the triangle under the crosshairs, edit the appropriate text widget. When satisfied with the values, select the SET button at the lower left, and the model will be updated.

5.1.2.3 Adding knotpoints

Toggle the ADD KNOTS button in the EDIT pulldown to the *'on'* setting. Reposition the pointer within the interior of the model where you wish to add a knotpoint and then strike the 'a' key. A new knotpoint will be added at the crosshairs, and new sides will form making three triangles from what was once one.

5.1.2.4 Creating discontinuities and changing sets

Select the MODEL button in the EDIT pulldown. A popup entitled "Edit Model" will appear:



and you will find that the right mouse button has been activated (but don't test it just yet). If you are not in flattened display mode, the program should complain -- this feature is designed only to work when the model is flattened. So if you didn't happen to be in flattened mode, toggle the FLATTEN button in the VIEW menu to *'on'* and try selecting the MODEL button again.

Move the pointer to where you would like to begin to add a string of knotpoints or perhaps form a discontinuity, then click and drag the right mouse button. A "rubber band" will stretch from where you started to wherever you now drag the pointer. When you release the mouse button, the line segment is frozen at that position. You may add other line segments by repositioning the pointer and single clicking the right mouse button. If you wish to enclose the region, select the CLOSE BUTTON, and a segment will be drawn from the last point to the beginning point. If you make an error and wish to begin again, simply select the CLEAR button. This will function until you go to the next step involving the ADD DISCON and ADD KNOTS buttons.

There are now three possibilities for proceeding. (1) If you have closed the polygon and wish to change the properties of all knots and triangles within the enclosed region but do not wish to add knots or discontinuities, go now to the top of the "Edit Model" popup where there are a set of five text widgets for v_p, v_s, ρ, Q_α, and Q_β, and three pushbuttons, SET, ADD and MULTIPLY. You can alter the values of current selected knots and triangles in the three ways suggested by the buttons. To set the absolute value of the parameters, enter those new values in the text widgets, and select SET. To increment them by a certain amount, enter that amount and select ADD. To apply a scale factor, enter that factor and select MULTIPLY. If the text widget is left blank, that value will not be altered.

(2) If you wish what you have drawn to be a simple, second order discontinuity in velocity (*i.e.*, continuous velocity but discontinuous first derivative) hit the ADD KNOTS button, and the model will reform either by moving knots onto the new segments if they

are very close or by creating new knots. The program ignores values in the parameter text widgets at the top. Values for v_p, v_s, ρ, Q_α, and Q_β are derived by linear interpolation or direct transfer from the parent knots and triangles.

(3) If you wish to create the usual kind of discontinuity (in both velocity and its derivative), choose ADD DISCON, and the model will be reformed in a fashion similar to the ADD KNOTS response. However, this time co-located knots are created to form the discontinuity. Unhappily, since the parameters of these knotpoints are also set by linear interpolation, the co-located points have the *same* values, *i.e., the velocity does not increase discontinuously.*

To resolve this inconsistency, the velocities and densities on one side of the discontinuity may be changed one knotpoint at a time as described in Section 5.1.2.2 or by selecting all triangles within the new discontinuity. This later process will now be described. Try to form an enclosed discontinuity as a trial.

One can change all the properties of the interior of that new discontinuity by moving the pointer into the interior and striking the letter *'s'*. It should change background color. Now go to the top of the "Edit Model" popup where there are a set of five text widgets for v_p, v_s, ρ, Q_α, and Q_β, and three pushbuttons, SET, ADD and MULTIPLY. As in (1) above, you can alter the values of current selected knots and triangles in the three ways suggested by the buttons. To set the absolute value of the parameters, enter those new values in the text widgets, and select SET. To increment them by a certain amount, enter that amount and select ADD. To apply a scale factor, enter that factor and select MULTIPLY. If the text widget is left blank, that value will not be altered.

5.1.3 Model output

Once velocity model editing is complete, one may store the altered model for future use by selecting the SAVE button in the FILE pulldown of the main meun bar. A popup entitled "Xgbm OutfilePrompt" should appear. If the default string in the text widget is not what you wish to use for your output file name, delete it by moving the pointer into the text widget, double clicking on the text (it should change to reverse video), and striking the *delete* key. The string should disappear. Enter the output file name you wish to use and append a .gb suffix. Select the OK button at the bottom. The model will be preserved in the directory pointed to by the GBWORKENV environment variable. (See Section 4.) To recover this model, see Section 5.1.1.2.

5.2 Source/Receiver Manipulation

It is possible to add, delete, and reposition sources and receivers in several ways:

5.2.1 Adding/deleting sources

Select the VIEW pulldown from the main menu and then select SOURCE. A further pulldown menu with the buttons ADD, DELETE, DELETE ALL, and LOCK should appear. To add a source, select ADD. A small star should appear at the X=0.0 coordinate at a depth that will depend on the maximum depth of your model. You may add more than one source, but rays will be traced only from the most recently added or relocated source. Selecting DELETE will delete the most recently added source. Selecting DELETE ALL will delete all sources.

5.2.2 Adding/deleting receivers

Select the VIEW pulldown from the main menu and then select RECEIVER. A further pulldown menu with the buttons ADD, ADD STRING, DELETE and DELETE ALL should appear. To add a single receiver, select the ADD button. A small filled triangle should appear at the free surface. To delete one or more receivers, select DELETE or DELETE ALL, respectively. To place a string of receivers, select the ADD STRING button. A popup entitled "Receiver String" should appear. In this popup are three text widgets labeled from top to bottom *Min distance, Spacing,* and *Num receivers*. Each may be edited. The units and the frame of reference for the first two depend upon the state of the KM and RELATIVE toggles of the "coordinates" popup. See Section 5.2.3 for more information. When you select the APPLY button, the popup will disappear and the receivers will be added.

5.2.3 Repositioning sources and receivers

The simplest way to move a source or receiver is to position the pointer near, depress the left mouse button and drag the symbol to the desired location. Care must be taken, because the symbol to be moved, source or receiver, will be the one closest to the pointer. It is therefore possible to move a receiver when one really wishes to move the source, or *vice versa*, unless one uses adequate caution. It is possible to move the source beyond the model boundaries, but if left there, no rays may be traced from it. In either display mode, receiver symbols are constrained to move along the free surface only. In earlier versions when in "spherical" display mode, receivers could be dragged anywhere, but when the mouse button was released, they would "snap" to the nearest point on the free surface.

There are many times when greater precision is required. Select the COORDS button in the VIEW pulldown. A popup entitled "coordinates" should appear. Now reposition a source or receiver as described in the preceding paragraph and watch as the text widgets of the popup are updated. (If you have no source or no receiver, that widget should be blank.) The coordinates displayed are for the source or receiver most recently added or moved.

There are two toggle buttons called KM and RELATIVE at the bottom of the popup. When *'on'* (default) KM means the receiver coordinates will be expressed in km, when *'off'*, in degrees. The frame of reference for the receiver positions is set by the RELATIVE toggle. When *'off'* (default), the frame of reference is relative to the model coordinate origin. When *'on'* the frame of reference is relative to the source's current horizontal coordinate. To position a source or receiver at a precise spot, edit the *source depth* and *receiver position* text widgets, and then select the SET button at the bottom. The position of the most recently added source and receiver will be updated accordingly. Note, therefore, that if you wish to place precisely more than one receiver, it is necessary to add one at at time, using the SET button to place each one immediately after it is added.

5.2.4 Using geotool to positioning source and receivers

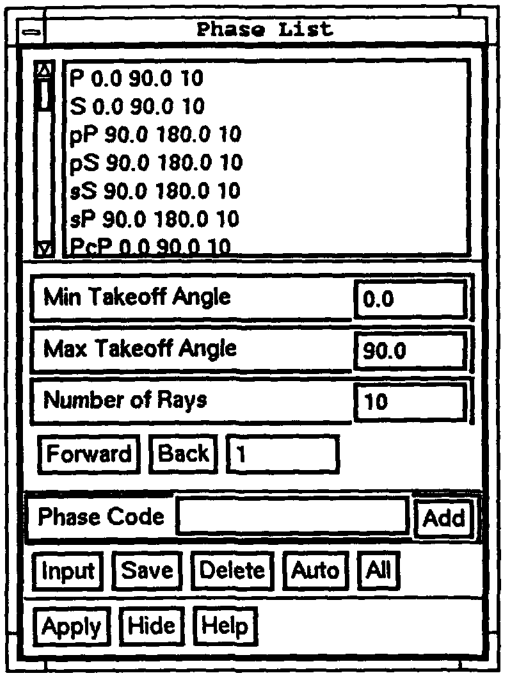
[Isis or ipcc IPC mode only!] It is possible to construct a display which accurately reflects (as far as is possible in 2-D) the source-receiver geometry of the data you are reviewing. For this function to work properly, one must be running *geotool* and *Xgbm* in an IPC mode, *geotool* must have origin information (*i.e.*, it must have an origin file) for the data, and *Xgbm* must be currently displaying a velocity model wide enough to accommodate the maximum source-receiver separation. First examine the waveform data you wish to model using *geotool*. Select those traces you wish to model, and then bring up limit lines by striking the *'l'* key. Position the limit lines to bracket the time segment you wish to model. Now direct your attention back to *Xgbm*. Select the OPTIONS button in the main menu bar, followed by QUERY GEOTOOL. The following should happen: (1) *Xgbm* deletes sources and receivers in the display, (2) *Xgbm* sends an IPC query (*SelectedWaveforms* in Appendix A) to *geotool* asking for the source-receiver location information, (3) *geotool* sends *Xgbm* a reply (also called *SelectedWaveforms*), (4) *Xgbm* plots a source at the x=0, z=source depth coordinates, and (5) *Xgbm* plots receiver symbols at distances corresponding to *geotool*'s IPC reply. Note that all azimuthal information is lost -- receivers located at azimuths diametrically opposite the source may in fact plot very close to one another in the *Xgbm* display..

5.3 Phase Selection

Once a velocity model is read in and modified as necessary, and once a source is placed, the user is ready to perform raytracing. To do so it is necessary to select the phases to be traced. These fall into three categories: phases with conventional names which appear in *Xgbm*'s default list, phases with conventional names which are not in *Xgbm*'s default list, and phases for which there is no convention. For the following tutorial, it would be useful to read in a *jb* velocity model extending down to include the inner core with a full 360° breadth. Place a source in the mantle.

5.3.1 Standard phases in list

Select OPTIONS followed by PHASE LIST. A popup entitled "Phase List" should appear:



At the top of this popup is a scrollable list with a large number of entries in it. Each entry consists of a common phase name followed by three numbers. Look at the first element of the list: "P 0.0 90.0 10". This is to indicate that ten rays of the phase *P* are to be traced from a takeoff angle of 0° (straight down) to 90° (counter-clockwise). Select this item now, and then select the APPLY button at the extreme lower left of the popup. A number of rays, blue in color if you have a color display, should be plotted outward from the source. Careful inspection will show that they do not number ten, as expected from the list item. *Xgbm* will not plot rays which do not fit its ray description. Consider the *P* ray which began at takeoff angle 0°. The ray is traced directly downward until it encounters a discontinuity, the core-mantle boundary in this case. Because it is named *P* and not *PcP* or *PKP*, tracing ceases at this point and no segment of the ray is plotted. Try a few other examples. You can plot more than one ray type by holding down the *Control* key as you make your picks. Do not forget to select APPLY to plot the rays. Note the *S* rays segments are plotted in red.

It is frequently essential to edit the takeoff angles and number of rays to be plotted for each phase. Select and plot *PKP* at a source depth of 100 km for example. There is only one ray plotted for the entry "PKP 0.0 90.0 10". Direct your attention to the central portion of the "Phase List" popup where there are located three text widgets labeled *Min Takeoff Angle, Max Takeoff Angle,* and *Number of rays.* Edit these values to 5.0, 30.0 and 20, respectively. As you change each text entry, all selected items in the list (in this case the *PKP* entry only) will now change to reflect the text widgets' current values. The rays will not be retraced until you select the APPLY button below or until you move the source. Select APPLY now and observe that many more rays are plotted and both the AB and BC branches of *PKP* are traced.

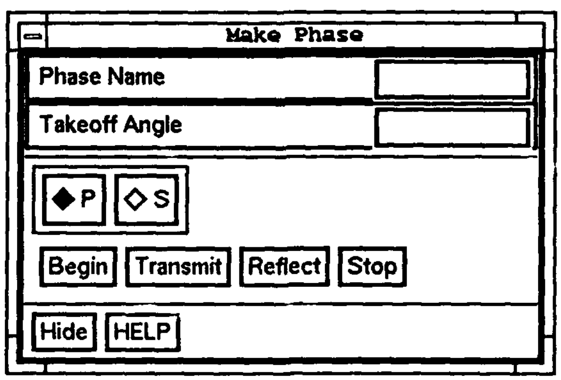
There is yet another useful feature in this popup which can now be illustrated. Add a receiver and position it at a distance so that at least one *PKP* ray terminates on either side of that receiver. Then select the AUTO button in the second row from the bottom. This initiates a primitive search routine to refine the takeoff angles, traces new rays based on the solution found by the routine, and updates the list entry. This will work for multiple phases provided each phase has rays which bracket the receiver. Further, if more than one receiver is displayed, the initial rays given the routine must bracket the distance spanned by the nearest and furthest receivers.

5.3.2 Standard phases not in list

Select OPTIONS followed by PHASE LIST as in Section 5.3.1. In the "Phase List" popup which appears, direct your attention to the third row from the bottom where a text widget labeled *Phase Code* to the right of which a pushbutton ADD are located. Enter PPP in the text widget, and select ADD. The entry "PPP 0.0 90.0 10" should be added to the top of the list of phases. Select the PPP item now and then hit APPLY at the extreme lower left. A number of PPP rays should now be displayed. See Section 5.3.1 for many details of how to change the takeoff angles and number of rays.

5.3.3 Non-standard phases

For many models, especially those with many discontinuities and those in 2-D and 3-D, it is difficult to plot a number of phases that are nevertheless of considerable importance to research and analysis. *Xgbm* gives the user the capability to create these phases, name them, and then preserve them for future use. First, bring up the "Phase List" popup as explained in Section 5.3.1. Now select EDIT from the main menu bar, followed by MAKE PHASE. A popup entitled "Make Phase" should appear:



It consists of two text widgets labeled *Phase Name* and *Takeoff Angle* at the top, a row of two toggle buttons labeled P, S, below them, and a row of four pushbottons, BEGIN, TRANSMIT, REFLECT, and END below them. To create a ray, it is necessary for the user to give *Xgbm* a paradigm for it to duplicate. That is, one must trace a ray through the model, specifying a ray type for each segment (defined as that portion of a trajectory between discontinuities) until that ray terminates at the free surface. As an example, first position your source just below the free surface. Now give the phase a name (limit this to less than 32 characters, please) and an initial takeoff angle by putting entries in the text widgets. A good illustration is to use a takeoff angle of 5° or 10°. Now choose whether the ray is to begin as a *P* wave or an *S* wave by selecting the appropriate toggle button. These two buttons function as radio buttons, *i.e.,* their selection is mutually exclusive. Now hit BEGIN. The program should plot a ray segment that extends from the source symbol down to the first discontinuity below the source, probably the 15 km deep Conrad discontinuity if you are using the *jb* model and have placed your source at depth less than 15 km. You must now decide where you want the phase to travel. Try selecting REFLECT. *Xgbm* should plot a second segment that goes up to the next discontinuity, the free surface. Had you hit TRANSMIT instead, the ray should have traveled to the Moho and stopped to wait for user instructions. Try a number of possibilities for reflection/transmission and ray type. If you make a mistake, simply reset your initial setting and hit BEGIN again. When you are finished, select END. As long as the ray terminates at the free surface (*Xgbm* will complain otherwise), the phase you have named will be prepended to the phase list in the "Phase List" popup. You may manipulate the new phase using "Phase List" just as you would the conventional phases in the list.

You may retain the phases you have created and any takeoff angles you have adjusted for conventional phases by selecting the SAVE button in the "Phase List" popup. A popup labeled "Save Selected Phases" will appear. Enter a filename in which you wish to save the list, and hit APPLY. The list will be saved in that file. To recover the list, select INPUT in the "Phase List" popup. A popup labeled "Input User-Defined Phases" will appear. Enter the filename of the file in which you have saved your phases in the text widget and hit APPLY. The phase list will be updated accordingly. Please remember that these phase definitions are tied to a specific velocity model that, in principal, may deviate very much from a laterally homogeneous model. *Xgbm* makes no check for user error.

It is possible to view the traveltime curves for selected phases. Select OPTIONS followed by TRAVEL TIME CURVES. Be sure you have one or more phases selected in the phase list. Now select the APPLY button in the "Phase List" popup. Traveltime curves should appear on the display. Now change the source depth. A second set of curves should be superimposed on the display. To prevent superposition, toggle the AUTO CLEAR button to *'on'*. Then each time the source is moved or the APPLY button is selected, the traveltime display will be cleared before the new curve or curves are plotted.

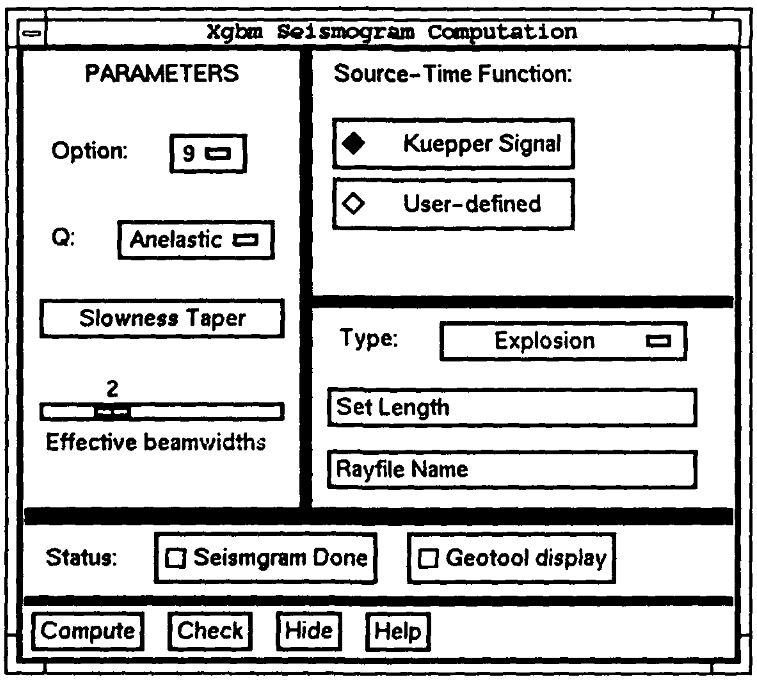
5.4 Seismogram Computation

Once raytracing has been performed, there is one critical action required of the user before seismograms may be computed: the raytracing results must be stored to a disk file. This is controlled by a toggle button in the FILE pulldown called WRITE. When this toggle is *'on'*, the raytracing results are written to a file named by default *rays.out* in the

GBWORKENV directory. (How to use another name is explained below.) The default position of the WRITE toggle is *'on'* so that novice users will not lose their raytracing results by mistake or worse, use results from an earlier worksession. *Xgbm* will run a bit faster with WRITE in the *'off'* position however. The user can experiment with which rays to include and their number and takeoff angles, then toggle the WRITE button back to the *'on'* position and all rays currently traced will be written to disk. While *'on'*, any alteration in the source position or hitting the APPLY button in the "Phase List" popup will cause the ray output file to be re-written. Therefore if one wishes to retain the ray-tracing results for a particular model, source position and phase selection, it is prudent to select a unique name for the output file and to change that name before altering any of the above. The WRITE toggle has occasioned considerable confusion among users of the beta release of *Xgbm*, but has been retained for flexibility.

The raytracing output file contains information about the source position and the ray-tracing results, but nothing about the receiver location(s). *GBseis* can access this file and use it to respond to queries for phase traveltime. However, in order to use *Xgbm* as a preprocessor for *GBseis* to compute a synthetic seismogram, it is first necessary to have at least one receiver in the display. Before continuing with this portion of the tutorial, check to be sure you have at least one receiver visible, and if not, add one. (See Section 5.2.2.)

Now select OPTIONS followed by COMPUTE SEISMOGRAM. A popup entitled "Xgbm Seismogram Computation" should appear:



This button is used by *Xgbm* to construct a message to *GBseis* telling *GBseis* how to compute the seismogram. If *Xgbm* is running in an IPC mode, either with *ISIS* or with *ipcc*, this information will be passed by IPC message. (See Appendix A - *Dogbseis*.)

Otherwise, *Xgbm* creates a small file and spawns an instance of *GBseis* to carry it out. All of this is invoked by selecting the APPLY button in the lower left.

But first, it may be necessary to adjust the parameters. Every button above the second row from the bottom controls parameters effecting seismogram computation. OPTION at the top left is how one choose from the nine possibilities *Weber* (1988a) offers for computing the Gaussian beam parameter ε. The reader is referred to Weber's paper especially pages 13-15 for a fuller explanation of their meaning. Option 9 is the default. If options 1-3 or 6 are selected, values for ε_1, ε_2 and the beamwidth g_L are solicited via popups.

Xgbm/GBseis can compute seismograms with or without the effects of Q. The default is the anelastic case. To ignore absorption and dissipation, select the button ANELASTIC and two buttons will appear -- ANELASTIC and ELASTIC. Release the mouse button on ELASTIC. To go back, reverse the procedure.

Sometimes when using very broad Gaussian beams, it is necessary to use slowness tapers to reduce numerical instability. These are invoked by selecting SLOWNESS TAPER. A popup entitled "qtaper" should appear with four text widgets labeled *q1-q4*, one toggle button ACTIVATE, and two pushbuttons, HIDE and HELP. The taper is a cosine taper with one limb between q1 and q2 and a second between q3 and q4. The ACTIVATE toggle controls input to the text widgets and whether this information is used by *Xgbm* or not. In the default *'off'* position, one cannot enter or edit what is in the q1-q4 text widgets, and *Xgbm* will ignore this information when composing its message to *GBseis*. In the *'on'* position, text may be entered and will be used in the computation.

The slider labeled *Effective beamwidths* allows the user to override a default. Normally, *GBseis* will only sum beams which terminate within two effective beamwidths of the receiver. (See *Weber*, 1988a.) By placing the pointer over the slider and depressing the left mouse button, this may be adjusted at between 1-5.

The radio buttons in the partition called "Source-Time Function" allow the user to control the shape and duration of the source wavelet. Selecting either KUEPPER SIGNAL or USER-DEFINED will cause a popup entitled "Kuepper signal" or "Xgbm Src-Time Funct Input", respectively, to appear. Which one *Xgbm* uses is governed by which radio button is currently on. The shape of the Kuepper signal wavelet (*Küpper*, 1958) is set by specifying its period T (duration in the popup) and an integer n (shape in the popup):

$$f(t) = sin(\, n\pi \frac{t}{T}) - \frac{n}{n+2} sin(\,(n+2)\,\pi\, \frac{t}{T}), \qquad 0 \le t \le T$$

Simply put, $n=1$ is a one-sided wavelet, $n=2$ is two-sided, *etc.*

In order to give the user greater flexibility, the USER-DEFINED button was included. The user first creates a file in which a time series of arbitrary complexity is written in ASCII free format. The name of this file is input into the text widget of the "Xgbm Src-Time Funct Input" popup and will be registered with *Xgbm* when the ACCEPT button of that popup is selected. That file will not be read, however, until

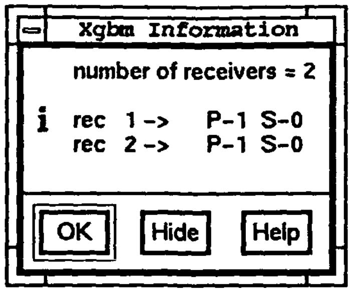
GBseis is ordered by *Xgbm* to use it. This will happen only if the USER-DEFINED toggle is on when APPLY of "Xgbm Seismogram Computation" is selected. *Xgbm* sets the sampling interval for this source wavelet from the data it is currently modeling or from the "Seismogram length" popup. (See below.)

Source type may be set via the type pulldown. Click on the EXPLOSION button and a cascade will appear with buttons for each possible source type: EXPLOSION, LINE SOURCE, and DOUBLE COUPLE. Releasing the button on any sets that type. As DOUBLE COUPLE is selected, a popup entitled "Xgbm Focal Mechanism" will appear. This popup contains four sliders, one for each parameter in a focal mechanism. The convention utilized is that of *Aki and Richards* (1980), pp. 105-115. Normally azimuth defaults to zero. If an IPC message has been exchanged with *geotool*, that value is updated to reflect the azimuth of the station first selected in the *geotool* display. These values will be used only if the DOUBLE COUPLE button is selected when APPLY is hit.

The user may wish to control the beginning time T_0 (relative to origin time), sampling interval *dt*, and duration *npts**dt*, of the time series to be calculated. *Xgbm* normally establishes the following priorities to determine these values: (1) If the user is currently modeling data based upon a query to *geotool*, this information is derived from the IPC message (*SelectedWaveforms*) in reply. (2) *Xgbm* examines all rays terminating within the number of effective beamwidths set by that slider and computes the minimum and maximum traveltime from this group to the current receivers. T_0 is set to 10% less than the minimum traveltime. *dt* is set to the Kuepper signal duration divided by twenty. Duration is set to 20% longer than the difference between minimum and maximum traveltime. (3) $T_0 = 0$, dt=0.1 sec, and duration is set to $dt/1024$. This may be overridden by selecting the SET LENGTH button. A popup entitled "Seismogram Length" will appear with three text widgets labeled *Npts, dt,* and *T0*. There is a toggle button ACTIVATE at the bottom. When ACTIVATE is in the default *'off'* position, the text widgets cannot be edited and *Xgbm* will ignore their values in constructing its message to *GBseis*. When *'on'*, the widgets are editable and will be used to override.

The RAYFILE NAME pushbutton and its associated popup "Xgbm Rayfile Name Input" were alluded to at the very beginning of this section. The name in the text widget of "Xgbm Rayfile Name Input" is used as the output file name for raytracing output. It may also be used to calculate seismograms for raytracing results computed much earlier and stored. Merely enter the filename of the earlier results in the widget, and the next time APPLY is hit, that file will be accessed by *GBseis*.

Once all the parameters have been set, *Xgbm* is ready to send its instructions to *GBseis*. One more check is in order, however. In order for *GBseis* to calculate accurately a phase's contribution to a seismogram, it is necessary for a number of rays (a good rule-of-thumb is five) of that phase type to terminate within the critical effective beamwidth limit, thereby giving an reasonable sample of the medium. The way to check how many have actually done so is to select the CHECK button at the bottom. A popup entitled "Xgbm Information" will appear:



For each receiver are listed the number and type of phases which terminate nearby. In this example, there are two receivers, each with one *P* ray and no *S* rays nearby. One should increase the number of rays calculated or narrow the takeoff angles in order to raise this level to five or greater.

Select the APPLY button in "Xgbm Seismogram Computation." The status display in the second row will change to reflect what is happening that is hidden from the user. Whether *'on'* or *'off'* before APPLY was selected, the SEISMOGRAM DONE button should be *'off'* immediately afterward. It will blink *'on'* again when *GBseis* has completed its calculation. If running in either IPC mode, *Xgbm* will immediately send an IPC message (called *wfdisc_3.0* in Appendix A) to *geotool* to display the newly-calculated synthetic seismogram, and the GEOTOOL DISPLAY button should blink *'on'*. *geotool* should display the calculation momentarily.

The parameters in this popup can be readjusted at this point and a new seismogram computed immediately. Only if the source is repositioned or if the velocity model is changed is it necessary to re-write the raytracing output file before continuing. It is instructive to make successive calculations, changing only the Kuepper signal duration or switching from elastic to anelastic computations.

The following note applies to naming the seismogram output files. In order to avoid name conflicts by repeated calculations in one or more work sessions, *Xgbm* constructs unique names for the output synthetic seismogram files from its process id number and an internal counter. A typical basename for output might be *syn_2537_3* where 2537 is the process id for the current run of *Xgbm* and 3 indicates this is the third seismogram computed in this session.

5.5 Color Display

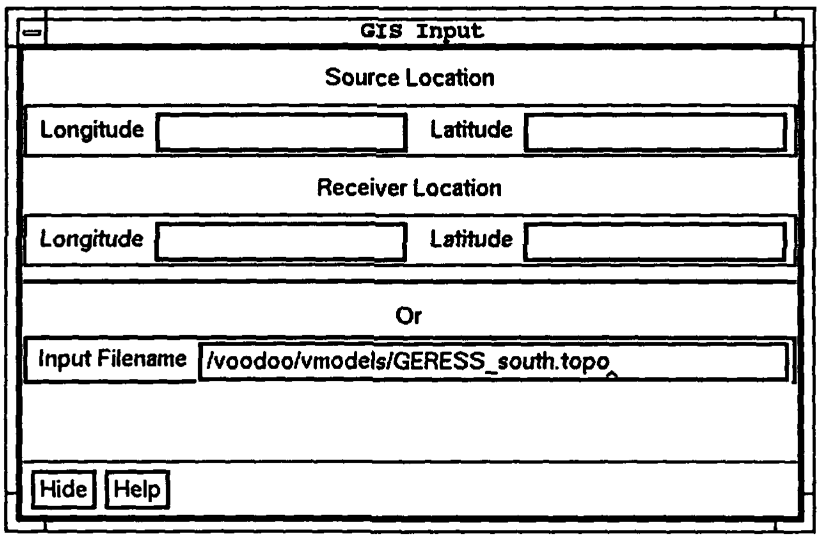
The background may be changed to colors proportional to v_p, v_s, or ρ by choosing the appropriate pushbutton in the COLOR pulldown of the VIEW menu. The actual colors used are controlled by the file xgb.rgb which, for this version of *Xgbm* must be located in the current working directory. The file consists of three columns of numbers that represent intensities of red, green and blue. The xgb.rgb file distributed with this release is not coded to a particular velocity scheme, so the user will certainly wish to change the colors to assemble a satisfying display.

The number of colors a workstation can handle is hardware dependent. Please consult your system administrator for what that value is. A similar file called rgb.txt comes with releases of X and associates common names with the three-color intensity codes. That file is found in the /usr/lib/X11 directory.

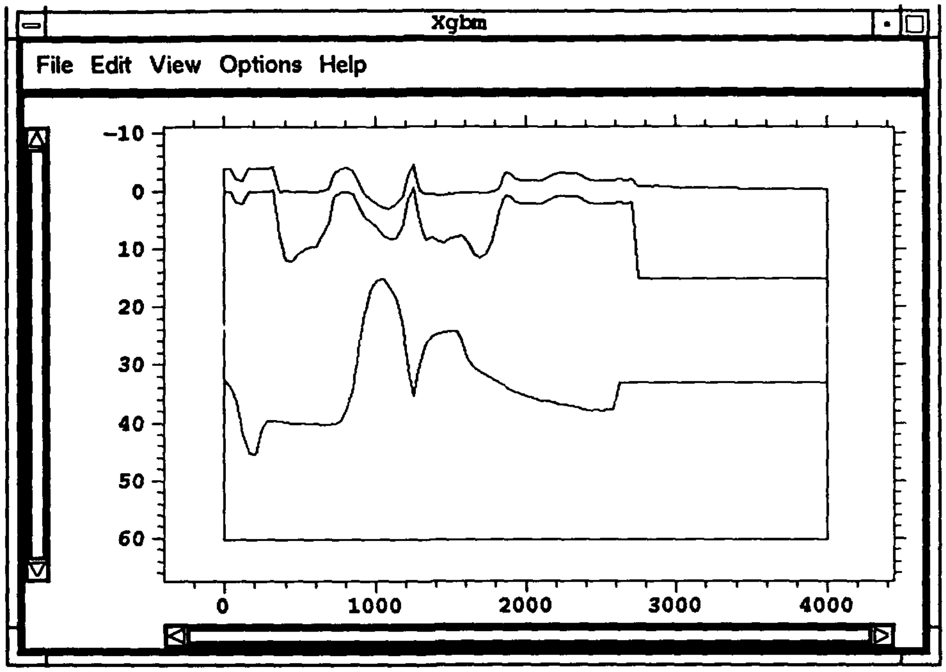
5.6 Interfacing with GIS

Users with an Internet address may take direct advantage of the capability to extract topography and moho-depth information contained in databases to which CSS users have access. Those users who do not have access may still exploit this feature of *Xgbm* by creating input files of the format described in Appendix B. This section of the tutorial makes use of such a file, *GERESS_south.topo*, found in the vmodels subdirectory, but the direct database connection will be described as well.

Click first on FILE followed by SET GIS. The popup "GIS Input" should appear:



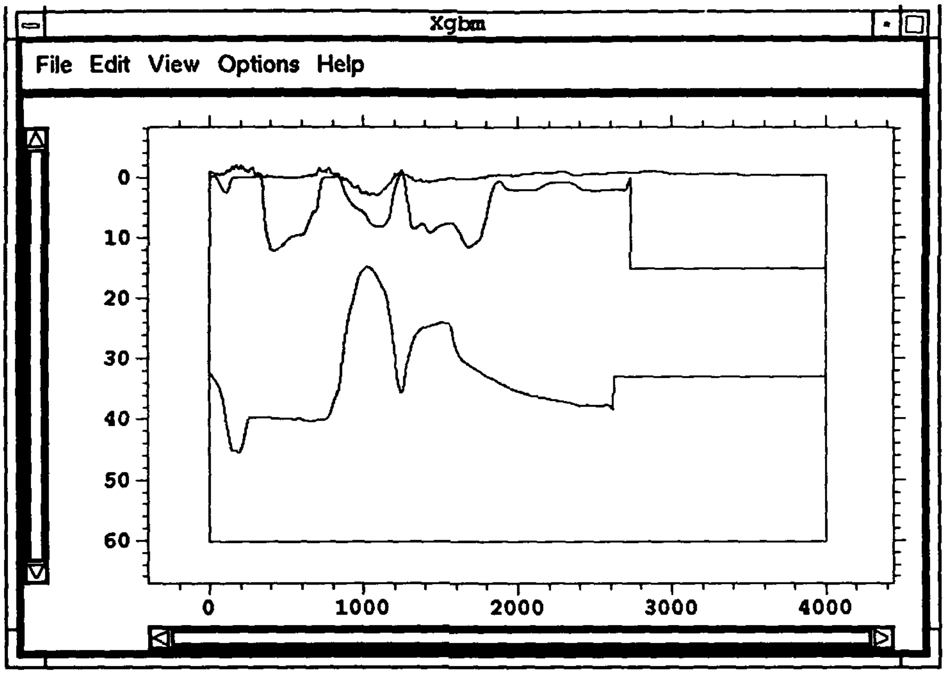
Enter the string /voodoo/vmodels/GERESS_south.topo in the Input Filename text widget and then press HIDE. (As the name suggests, GERESS_south.topo is a representation of structure to the south of the GERESS array and is shown also in *Davis and Henson,* [1993].) Now click on the FILE pulldown again, and this time, toggle the USE GIS button to *'on'*. Now choose FILE followed by INPUT and then STANDARD. When the "Xgbm Model Choice" popup appears, choose the Global jb model, and set the depth to 60 km, the breadth to 4000 km, and the number of knots to 100. Hit APPLY. Because you have set the USE GIS button to *'on'*, *Xgbm* is forced to check the "GIS Input" popup for topography data. Since you have filled in the Input Filename widget of "Xgbm Model Choice", *Xgbm* will read that string and try to open a file of that name. The model to appear should look like:



This rendering of the topographic data contained in GERESS_south.topo is unsatisfactory as a check of the data in the file will reveal. The horizontal lines on the right side beginning at about x=2600 km occur because data for the second and third discontinuities do not extend along the entire 4000 km section. At the point in the cross-section where depth values terminate, *Xgbm* begins abruptly to use the original model basis depths, in this case, 15 km and 33 km.

More problematical is that the surface topography has been distorted by *Xgbm*'s attempt to accommodate undulations in the second layer where it is very near the surface. *Xgbm* acts to prevent the aspect ratio of its constituent triangles from becoming too severe, and in this case, the consequence is to push the topography up too far. That is, a minimum thickness for the layer is established, and where the trial thickness is less than that minimum, the surface is pushed upward.

This is a problem of resolution and can be corrected by increasing the number of knotpoints. Click on FILE followed by INPUT and then STANDARD. This time change the number of knots to 1000, and then hit APPLY. The new rendering should look like:



This is a much more faithful representation of the database information.

Had the user wished to obtain a different cross-section, the appropriate action is to fill in the Source and Receiver Latitude and Longitude of the "GIS Input" popup. These two pairs represent the endpoints of the cross-section. One may enter the cross-section endpoints or a file name but not both. If the endpoint coordinates are entered and the USE GIS toggle is on, then when the APPLY button of the Xgbm Model Choice" popup is pushed, *Xgbm* spawns an *gc_raster* process which will connect to a database and write a file called Xgbm.gis which is then read by *Xgbm*. Just which machines and databases are contacted are specified as resources in the X resource file XgbmFirst as Xgbm.gisServers. The resource is typically a series of lines such as

host=129.236.10.55 view=dbdb5 discon=surface,...

in which one specifies the Internet address of the machine containing the database desired, the name of the database, and the name or number of the discontinuity to which the extracted information should be applied.

Whether utilizing the Internet connection or simply reading topography information from a local disk file, it is necessary to use a 1-D starting model as a basis. The creation of model topography takes place as the 1-D model is stretched into 2-D. Trying to incorporate topography into a 2-D model created in an earlier worksession will have unpredictable results.

6. COMMON ERRORS AND PITFALLS

Considerable effort has been made to write the best code possible given the resources available for this project. In particular, one of the principal design goals was to make the package as easy to use and with as seamless an interface to other programs as is possible. However, even with more than 10^4 lines of code, the diverse demands of the research and analysis community will certainly outstrip this package's capabilities. Some pitfalls listed here may seem silly given all the other checks the programs automatically make, but many are rooted in the package's internal architecture. All were addressed as resources permitted.

(1) When using *geotool*, trying too narrow a velocity model. If the maximum separation or receivers being viewed by *geotool* is 10,000 km and you have a model only 7,000 km in breadth, *Xgbm* will issue an error message.

(2) Forgetting what rays you have written out. It is easy to adjust the takeoff angles of one phase in the list, then select another (de-selecting the first phase in the process), and write its results out. Unless you have both phases selected when you write the raytracing results to file, your seismogram may contain the one chosen but not the other.

(3) Overwriting old seismograms. This problem has been largely solved in Version 1.1. Earlier versions may give some difficulty.

(4) Although *Xgbm* has the capability to display more than one source at a time, its behavior is unpredictable in most cases when more than one source are handled. Please use great caution.

(5) Adopting too little model resolution when high relief topography is to be placed on thin layers. *Xgbm* acts to prevent the creation of triangles with unfavorable aspect ratios. This problem has been illustrated in Section 5.6.

7. BUTTON ACTIONS

This section is to provide a reference for how *Xgbm* responds to the selection of its buttons. The main menu bar consists of the buttons FILE, EDIT, VIEW, OPTIONS and HELP. Selection of any of these will cause a pulldown menu to appear. With the exception of HELP the consequences of selecting a button are detailed below.

7.1 FILE Pulldown Menu

INPUT - for reading in velocity models; causes pulldown menu to appear.
INPUT:STANDARD - manages "Xgbm Model Choice" popup.
INPUT:USER-DEFINED - manages "User-defined Models" popup.
SAVE - for saving velocity model to file; manages "Xgbm OutfilePrompt" popup.
WRITE - toggles writing raytracing results to file.
USE GIS - toggles use of GIS software to input information on topography
SET GIS - manages "GIS Input" popup.
PRINT - manages the "Model Print" popup.

QUIT - halts program execution.

7.2 EDIT Pulldown Menu

MAKE PHASE - for composing non-standard phases; manages "Make Phase" popup.
MOVE KNOTS - toggles ability to move knotpoints
ADD KNOTS - toggles ability to add knotpoints at location of crosshairs with the 'a' key..
MODEL - for creating irregular discontinuities; manages "Edit Model" popup.
PARAMETERS - for changing parameters of single knots; manages "changeVel" popup.

7.3 VIEW Pulldown Menu

SOURCE - causes pulldown menu to appear.
SOURCE:ADD - adds one source to velocity model display.
SOURCE:DELETE - deletes one source from velocity model display.
SOURCE:DELETE ALL - deletes all sources from velocity model display.
SOURCE:LOCK - toggle to freeze source at current coordinates
RECEIVER - causes pulldown menu to appear.
RECEIVER:ADD - adds one receiver to velocity model display.
RECEIVER:ADD STRING - for placing array; manages "Receiver String" popup.
RECEIVER:DELETE - deletes one receiver from velocity model display.
RECEIVER:DELETE ALL - deletes all receivers from velocity model display.
TRIANGLES - toggle for display of all model triangle sides.
CLEAR RAYS - clears display of all plotted ray trajectories.
FLATTEN - toggles display between "flattened" and "unflattened' (spherical).
COLOR - causes pulldown menu to appear.
COLOR:OFF - returns display to plain background.
COLOR:Vp - background color becomes proportional to v_p.
COLOR:Vs - background color becomes proportional to v_s.
COLOR:Rho - background color becomes proportional to ρ.
COORDS - for finding/setting coordinates; manages "coordinates" popup.

7.4 OPTIONS Pulldown Menu

PHASE LIST - for selecting phases to trace; manages "Phase List" popup.
COMPUTE SEISMOGRAM - manages "Xgbm Seismogram Computation" popup.
QUERY GEOTOOL - sends IPC message called *SelectedWaveforms* to *geotool* requesting src/rec coordinates.
TRAVEL TIME CURVES - for plotting traveltimes; manages "Travel-Time Curves" popup.

7.5 Xgbm Model Choice popup

DEPTH/RADIUS - changes axes' labeling of velocity and density plots.
KM/DEGREES - forces program to interpret text entry as km/degrees.
APPLY - implements model based on depth, breadth and resolution limits as set; unmanages "Xgbm Model Choice" popup.
HIDE - unmanages "Xgbm Model Choice" popup without implementing model choice.

7.6 User-defined Models popup

OK - program reads string in *Selection* text widget and attempts to open that file; unmanages "User-defined Models" popup. If the file opening succeeds and that file does contain a valid model, that model will be read in and displayed; if not, an error popup will appear.
FILTER - revises *Directories* and *Files* lists on the basis of the string in the *Filter* text widget.
CANCEL - unmanages "User-defined Models" popup without attempting to open and read any files.

7.7 Xgbm OutfilePrompt popup

OK - program attempts to write velocity model to file in directory set by GBWORKENV environment and named according to string in text widget; unmanages "Xgbm OutfilePrompt" popup.
CANCEL - unmanages "Xgbm OutfilePrompt" popup without attempting to open file.

7.8 Make Phase popup

BEGIN - program calculates and plots a ray segment beginning at the source and terminating at the first discontinuity the ray encounters. The ray type (*P* or *S*) is determined by the current state of the P/S radio button.
TRANSMIT - program calculates and plots the next ray segment beginning as a transmission through the discontinuity last hit and continuing until a new discontinuity, the free surface, or a model boundary is encountered. The new segment's ray type is set by the current state of the P/S radio button.
REFLECT - program calculates and plots the next ray segment beginning as a reflection from the discontinuity last hit and continuing until a new discontinuity, the free surface, or a model boundary is encountered. The new segment's ray type is set by the current state of the P/S radio button.
END - causes program to register phase internally and to append a phase name corresponding to string in *Phase Name* text widget to phase list

found in "Phase List" popup.
HIDE - unmanages "Make Phase" popup.

7.9 Edit Model popup

SET - reads current values found in the text widgets of this popup and updates currently selected knotpoints and triangles explicitly according to these values.
ADD - reads current values found in the text widgets of this popup and updates currently selected knotpoints and triangles by incrementing their current values by the text widget entries.
MULTIPLY - reads current values found in the text widgets of this popup and updates currently selected knotpoints and triangles by scaling their current values by the text widget entries.
CLEAR - cancels current knot segment creation.
CLOSE - program closes loop of tracing by connecting last point with beginning point, as long as the created segment does not cross earlier ones.
ADD DISCON - program creates discontinuity along tracing.
ADD KNOTS - program creates string of knots or repositions near knots along the tracing.
HIDE - unmanages "Edit Model" popup.

7.10 changeVel popup

SET - causes program to modify properties of knot according to values in this popup's text widgets.
HIDE - unmanages "changeVel" popup.

7.11 Receiver String popup

APPLY - causes program to place a string of receivers in pattern specified in text widgets. See Section 5.2.2.
CANCEL - unmanages "Receiver String" popup.

7.12 coordinates popup

SET - causes program to place source and/or receiver at coordinates of text widget entries and unmanages popup. If more than one source or receiver are present in the display, only the most recently added will be repositioned.
KM - toggle to force program to interpret text widget entries in this popup and in "Receiver String" popup as kilometers or as degrees. Default position is *'on'* (kilometers).
RELATIVE - toggle to force program to interpret text widget entries in this popup as relative to source or relative to velocity model

coordinate system (default). HIDE - unmanages the "coordinates" popup.

7.13 Phase List popup

FORWARD - program reads minimum takeoff angle from list entries, increments that number by value in text widget to right of BACK button, revises list entries and text widget entries, and plots a single ray of that takeoff angle if possible.
BACK - program reads minimum takeoff angle from list entries, decrements that number by value in text widget to right of BACK button, revises list entries and text widget entries, and plots a single ray of that takeoff angle if possible.
ADD - program reads string in *Phase Code* text widget and compares the string to phase list. If already there, program manages error popup, otherwise appends string to bottom of phase list.
INPUT - for importing phase description files; manages "Input User-Defined Phases" popup.
SAVE - for writing a phase description file; manages "Save Selected Phases" popup.
DELETE - delete selected entries from phase list.
AUTO - invokes primitive search routine for selected phases. Initial takeoff angles of selected phases must be so chosen that raypaths bracket receiver location(s). At least one receiver must be displayed.
ALL - select all phases in phase list.
APPLY - trace all rays of selected phases. If WRITE toggle button (from FILE main menu pulldown) is *'on'*, raytracing results will be written to file.
HIDE - unmanages "Phase List" popup.

7.14 Xgbm Seismogram Computation popup

OPTION - sets method of computing Gaussian beam parameter ε according to *Weber,* (1988a).
ANELASTIC/ELASTIC - toggle controls whether t^* operator is used or not.
KUEPPER SIGNAL/USER-DEFINED - toggle controls what type of source-time function is used. If KUEPPER SIGNAL is selected, the "Kuepper signal" popup is managed; if USER-DEFINED, the "Xgbm Src-Time Funct Input" popup is managed.
EXPLOSION/LINE SOURCE/DOUBLE COUPLE - sets source type; selecting DOUBLE COUPLE will cause the "Xgbm Focal Mechanism" to be managed.
SET LENGTH - for explicitly controlling time parameters of synthetic calculation; manages the "Seismogram length" popup.
RAYFILE NAME - for setting name of raytracing output file; manages the "Xgbm Rayfile Name Input" popup.

COMPUTE - initiates sequence to compute synthetic. Program interprets settings of widgets in this popup (and their associated popups), constructs a message to *GBseis*. Message is dispatched according to operating mode. See Section 5.4.

CHECK - for checking proximity of rays to receivers; manages the "Xgbm Information" popup.

HIDE - unmanages "Xgbm Seismogram Computation" popup.

7.15 Travel-Time Curves popup

CLEAR - clears traveltime display.

AUTO CLEAR - toggle to enable automatic clearing of display. When *'off'* (default), program superimposes curves from different models and source depths. When *'on'*, display is cleared each time before rays are retraced.

PRINT - manages the "Model Print" popup.

HIDE - unmanages the "Travel-Time Curves" popup.

7.16 Input User-Defined Phases popup

APPLY - read string in *Filename* text widget; attempt to open file of that name; if successful, read file and revise phase list accordingly.

CANCEL - unmanages "Input User-Defined Phases" popup without attempting to open any files.

7.17 Save Selected Phases popup

APPLY - read string in *Filename* text widget; attempt to open file of that name; if successful, write content of selected entries in phase list to file.

CANCEL - unmanages "Save Selected Phases" popup without attempting to open any files.

7.18 Kuepper signal

HIDE - unmanages "Kuepper signal" popup. These text widgets will be read by program when APPLY (from "Xgbm Seismogram Computation") is selected if KUEPPER SIGNAL is then *'on'*.

7.19 Xgbm Src-Time Funct Input popup

HIDE - unmanages "Xgbm Src-Time Funct Input" popup. The string in the *Filename* text widget will only be read by the program when

APPLY (from "Xgbm Seismogram Computation") is selected if USER-DEFINED is then *'on'*.

7.20 Xgbm Focal Mechanism popup

HIDE - unmanages "Xgbm Focal Mechanism" popup. These sliders will be used by program when APPLY (from "Xgbm Seismogram Computation") is selected if DOUBLE COUPLE is currently selected.

7.21 Seismogram length popup

ACTIVATE - toggle to control use of information in the three text widgets of this popup. If toggle is *'on'*, the text widgets may be edited, and this information will be used the next time the APPLY (from "Xgbm Seismogram Computation") button is selected. If toggle is *'off'*, widgets cannot be edited, and the program will ignore these entries.

HIDE - unmanages "Seismogram length" popup.

7.22 Xgbm Rayfile Name Input popup

HIDE - unmanages "Xgbm Rayfile Name Input" popup. If WRITE toggle (from FILE pulldown) is *'on'*, program will read string from text widget in this popup and attempt to write results to file of that name in directory set by GBWORKENV environment.

7.23 Xgbm Information popup

OK/HIDE - unmanages "Xgbm Information" popup.

7.24 GIS Input

HIDE - unmanages "GIS Input" popup.

8. KNOWN BUGS

These listed here are well recognized shortcomings, but unfortunately they generally cannot be addressed under the present system architecture. If the system is ever redesigned, effort will be made correct them.

(1) When the velocity model is shown in unflattened mode, the raypaths are displayed incorrectly. This display is based on rays traced through the flattened model. When rays are transformed for the unflattened display, they do not always meet the triangle sides.

The internal calculation is correct, however, and calculated traveltimes and synthetic seismograms are perfectly valid in both flattened and unflattened display mode. This irksome property diminishes somewhat with model resolution.

(2) When in an IPC mode, *Xgbm* uses the azimuth of the first station in the IPC message from *geotool* to calculate its seismograms for all stations. This particular value can be overridden in the "Focal Mechanism" popup, but it is still applied to all receivers without regard to their varying geometry. There is no satisfactory way, as yet, to project 3-D data onto a 2-D model with this system.

(3) There is currently no elegant way to terminate *GBseis* when it is running in IPC mode under ISIS. In Unix, one may use the kill command if one knows *GBseis*' process id number, or one may bring it to the foreground and kill it by typing the interrupt key.

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Appendix A. IPC Message Formats

Below is a table of messages exchanges, followed by a detailed description of its contents.

name	*originator*	*recipient*	*contents*
1. SelectedWaveforms	Xgbm	geotool	src/rec geometry request
2. SelectedWaveforms	geotool	Xgbm	src/rec geometry
3. Dogbseis	Xgbm	GBseis	computation parameters
4. Donegbseis	GBseis	Xgbm	output database name
5. wfdisc_3.0	Xgbm	geotool	syn database name
6. Errorgbseis	GBseis	Xgbm	error string
7. Timegbseis	-	GBseis	traveltime request
8. GBseistimes	GBseis	-	traveltime(s)
9. Quitgbseis	-	GBseis	quit command

The following are the message formats. Regular type represents that part of the message required of all messages of that name and is used by the program to parse the message. Italic type is that part of the message unique to each transmission. The order of elements in (2) is critical; that of (3) is not. In message (3), the rayfile name must be provided.

(1) "" (empty string)

(2) "num= *number of waveforms*
sta= '*sta (trace1)*'
chan= '*chan (trace1)*'
lat= *lat(sta-trace1)*
lon= *lon(sta-trace1)*
samprate= *samprate(trace1)*
t1= *beginning epochal time(trace1)*
t2= *ending epochal time(trace1)*
olat= *origin-latitude*
olon= *origin-longitude*
depth= *origin-depth*
otime= *origin epochal time*
narr= *number of arrivals(trace1)*
phase= '*first phase name(trace1)*'
time= *first arrival time(trace1)*
phase= '*second phase name(trace1)*'
time= *second arrival time(trace1) ...*"

(3) "rayfile= "*raytracing input filename*"
dir="*output file prefix name*"
dfile="*output directory name*"

stfunc="*name of file containing source-time function*"
ls=*number of points in time series*
dt=*sampling interval in seconds*
tmin=*offset time from origin*
vred=*reduction velocity (km/sec)*
t=*duration of Kuepper signal (Section 5.4)*
n=*shape of Kuepper signal (Section 5.4)*
ndisp=*0/1 - ignore/include dispersion*
ipu=*0/1/2 - line source/point source/double couple*
iff=*1/2/3/4/6/7/8 - Weber option number 1,2,3/5/4/6/7/8/9*
ngb=*use every ngb'th ray in calculation*
nefv=*number of effective beamwidths to include*
gl=*beamwidth for option 6.*
eps1f=ε_1
eps2f=ε_2
stri=*strike of focal mechanism*
dip=*dip of focal mechanism*
rak=*rake of focal mechanism*
azi=*station azimuth for focal mechanism*
qmin=*lower half of lower limit on q taper*
qt=*upper half of lower limit on q taper*
qtt=*lower half of upper limit on q taper*
qmax=*upper half of upper limit on q taper*
olat=*origin latitude*
olon=*origin longitude*
otime=*origin epochal time*
nr=*number of receivers*
delta=*distance to first receiver (degrees), to second receiver ..., to nr'th receiver*"

(4) "*synthetic_seismogram_database_prefix*"

(5) "prefix= *synthetic_seismogram_database_prefix*"

(6) "*string describing error*"

(7) "rayfile= "*raytracing outfilename*"
phase= "*phase name (<= 32 characters)*"
nr= *number of receivers*
delta=*distance to first receiver (degrees), to second receiver ..., to nr'th receiver*
nefv= *number of effective beamwidths*"

(8) "times= *time_rec.1, time_rec.2, ...time_rec.nr*"

(9) "" (empty string)

Appendix B. File Formats

times.out - This file is opened by *Xgbm* at the same time raytracing results are written to file. It currently consists of six columns: phase name, distance (degrees), source depth (km), traveltime (seconds), slowness (seconds/degree) and t^*.

rays.out - This is the name of the default raytracing output file written in binary by *Xgbm* and read by *GBseis*. The name may be changed by the user at run time. The header to the file consists of five numbers:

double -- x coordinate of source
double -- z coordinate of source
double -- v_p at source coordinates
double -- v_s at source coordinates
double -- ρ at source coordinates

This is followed by a block of numbers for each ray. Each block consists of:

int -- indicates position in order of phases to be computed
float -- rate of change of starting angle between rays of this phase
int -- raytype at source: 1 for *P*, 3 for *SV*, 5 for *SH*
float -- takeoff angle (degrees)
float -- horizontal slowness at endpoint
float -- x component of unit tangent vector at endpoint
float -- z component of unit tangent vector at endpoint
float -- x coordinate of endpoint
float -- z coordinate of endpoint
float -- velocity at endpoint
float -- velocity gradient perpendicular to ray tangent at endpoint
float -- velocity gradient parallel to ray tangent at endpoint
float -- ρ at endpoint
float -- traveltime
float -- real part of product of reflection/transmission coefficients along ray
float -- imaginary part
float -- q_1 given at ray endpoint
float -- p_1 given at ray endpoint
float -- q_2 given at ray endpoint
float -- p_2 given at ray endpoint
float -- ε_1 - real part of beam parameter ε
float -- ε_2 - imaginary part
float -- number of caustics touched by ray (caustics of line-source-field)
float -- transversal spreading (point source)
float -- reciprocal of square of beamwidth at main frequency
float -- absorption parameter given at ray endpoint
float -- Q-factor at ray endpoint
float -- product of th/thti along ray
float -- real part of horizontal transfer function

float -- imaginary part
float -- real part of vertical transfer function
float -- imaginary part
char [31 bytes] -- phase name
Refer to *Weber* (1988a) for symbol definitions.

dot.**GB_input** - This input file name is fixed. The contents of the file should be a single string corresponding to the format of the *Dogbseis* IPC message in Appendix A. This file is written by *Xgbm* and read by *GBseis* only when the package is run in non-IPC mode.

velocity model input - While there is no rigid naming convention for these files, the *Xgbm* popup for inputing such a file is designed to find files ending in ".gb" faster. Each velocity model input file consists of columns of figures corresponding to depth, v_p, v_s, ρ, Q_α and Q_β, respectively. Two lines for the same depth indicate a velocity discontinuity. One should place lines with strings "mantle", "outer-core" and "inner-core" between tne lines representing these discontinuities. See Appendix C.

velocity model output - These are binary files intended for input by *Xgbm*. The header to the file consists of six numbers:
int -- set equal to 376482 to indicate model stored in binary format
int -- layer index of mantle- crust boundary
int -- layer index of core-mantle boundary
int -- layer index of inner core-outer core boundary
int -- number of knots in model
int -- number of triangles in model
For each knot, there follows a block with the following format:
float -- x coordinate of knot
float -- z coordinate of knot
float -- v_p
float -- v_s
float -- ρ
For each triangle, there are first blocks of this format:
int -- index of triangle's first knot (counterclockwise)
int -- index of triangle's second knot (counterclockwise)
int -- index of triangle's third knot (counterclockwise)
int -- index of triangle's first neighboring triangle (counterclockwise)
int -- index of triangle's second neighboring triangle (counterclockwise)
int -- index of triangle's third neighboring triangle (counterclockwise)
int -- type of discontinuity between this and first neighboring triangle
int -- type of discontinuity between this and second neighboring triangle
int -- type of discontinuity between this and third neighboring triangle
float -- Q_α for triangle
float -- Q_β for triangle

int -- code for crust, mantle, outer core, and inner core
char -- boolean code for whether that triangle was selected or not

and then blocks of this format:

double -- $\partial(v_p) / \partial x$
double -- $\partial(v_s) / \partial x$
double -- $\partial \rho / \partial x$
double -- $\partial(v_p) / \partial z$
double -- $\partial(v_s) / \partial z$
double -- $\partial \rho / \partial z$

The code for neighboring triangles and type of discontinuity uses the following convention: if the triangle is on the border of the model, the index value for the neighboring triangle is set to 333333333. If there are receivers located on that side, the neighboring triangle is multiplied by -1. The first neighbor is located on the side connecting the first and second knots, *etc.* If the discontinuity between the triangle and its neighbor is in the second derivative of velocity only, the type is set to zero. If the discontinuity is in the first derivative of velocity, the type is set to the program's internal index of that discontinuity. If the type is 222222, the triangle borders the free surface.

source-time function - These files are free format ASCII files and should contain only figures representing the time series of the source-time function. The file may be read in using the USER-DEFINED option when setting up the seismogram calculation in *Xgbm*.

xgb.rgb - This file lists the red-green-blue intensities for the colors used in velocity/density displays. Each line contains an integer triplet ranging from 0 to 255. The file is read until the hardware-dependent number of colors limit is met or the end-of-ifle is encountered.

GIS topography input - Files of this format are used to impose topography on velocity model discontinuities. The most common such file, *Xgbm.gis*, is generated by the routine *gc_raster*, but the user may input any similar file via the "GIS Input" popup's text widget. (An example file *GERESS_south.topo* is include in the vmodels subdirectory.) The file may have one or more blocks of lines. Each block consists of a header line composed of a string to identify the discontinuity and an integer to indicate the number of lines containing x-z coordinate pairs to follow. That is:

```
string_identifier.block_1 npts.block_1
x1(1) z1(1)
x1(2) z1(2)
 . . .
x1(npts.block_1) z1(npts.block_1)

string_identifier.block_2 npts.block_2
x2(1) z2(1)
x2(2) z2(2)
 . . .
x2(npts.block_2) z2(npts.block_2)

 . . .
```

The possibilities for the string_identifier are **surface, moho, CMB, ICOC,** and **discon=*n*,** where *n* is an integer to identify the discontinuity. In a 1-D model, the surface would be n=0, the first discontinuity below that would be n=1, *etc.*, so that entering

    surface 100

and

    discon=0 100

are equivalent. For correct parsing to take place, it is essential that no spaces be between "discon", "=" and the integer.

Under the present scheme, the x coordinate is given in degrees, and the z coordinate, in kilometers. The z coordinate increases with depth, so to impose surface topography above sea level, a negative z value must be used. This curious mixture of units makes little sense if one is working only near the surface, but since discontinuities can occur at a wide variety of depths, it is more uniform to express the coordinates in this way.

Appendix C. Velocity Models

The standard global models distributed with the software package are derived from published sources, either as such or as derived from traveltime tables.

abbreviation	*name*	*reference*
jb	Jeffreys-Bullen tables	*Jeffreys and Bullen*, 1940
herrin.abr	Herrin tables	*Herrin et. al.*, 1968
herrin.orig	Herrin tables	*Herrin et. al.*, 1968
1066a	Model 1066A	*Gilbert and Dziewonski*, 1975
1066b	Model 1066B	*Gilbert and Dziewonski*, 1975
prem	PREM	*Dziewonski and Anderson*, 1984
iaspei91	IASPEI 1991 tables	*Kennett*, 1991
pwdk	Model PWDK	*Weber and Davis*, 1990
afls	Model AFLS	*Schlittenhardt*, 1991
sp6	Model SP6	*Morelli and Dziewonski*, 1993

The abr and orig following herrin refer to abridged (smoothed over depths where the velocity gradient was small) and original, respectively. In those instances where a published model consisted only of seismic velocities, values for density were interpolated from PREM and values for attenuation were interpolated from the Q models of *Masters and Gilbert* (1983). The exception to this is SP6, for which the Q values were interpolated from PREM. Model AFLS is PREM with a crustal model appropriate for Pahute Mesa and an upper mantle (depth < 1271 km) Q structure from *Archambeau et al.,* (1969).

The global files are all stored in the */vmodels* subdirectory in a series of files all prefixed with "GB." (Your GBMODENV environment should be pointing to */vmodels*.) Each file consists of columns of figures corresponding to depth, v_p, v_s, ρ, Q_α and Q_β, respectively. Two lines for the same depth indicate a velocity discontinuity. Occasionally, one finds lines with strings like "mantle", "outer-core" and "inner-core" between lines of the same depth. These are used by the program to create an internal representation of phases.

It is possible to create one's own model with a file in this format. The program can read this personal model in in one of two ways. If you expect to use the model only occasionally, the easiest way is to read it in as a user-defined model, as explained in Section 5.1.1.2. A riskier way is to add it to the permanent list. **This should be done only by programmers experienced with X-Windows.** First, be certain your model file is in the */vmodels* subdirectory. Next edit the *XgbmVel* X-resource file in the *X11* subdirectory. Search for the string "globalSW.globals.items". There should be a list of models there. Add your model name, being certain to match the string to your file name. Now increase the integers in the two lines above, "globalSW.globals.itemCount" and "globalSW.globals.visibleItemCount" by the number of models you have added.

The list of regionals may also be altered. The displayed list is derived from the file *GB.regionals* in the */vmodels* subdirectory. Each line in the file contains information about a two-layer model over a half-space. The parameters are in the following order: top layer thickness, bottom layer thickness, v_p(top), v_p(bottom), v_p(mantle), v_s(top), v_s(bottom), v_s(mantle), ρ(top), ρ(bottom), ρ(mantle), Q_α(all), Q_β(all), and identification string. To add your model, simply edit this file and add a new line with its parameters.

Appendix D

A complete description of the CSS 3.0 format can be found in *Anderson et al.* (1990). Included here are tables only for *wfdisc*, *origin*, and *arrival* tables. The .wfiles, which the *wfdisc* files describe, are always written by *GBseis* in t4, *i.e.*, IEEE single precision floating point numbers.

Relation:		**arrival**			
Description:		Summary information on a seismic arrival			
attribute name	field no.	storage type	external format	character positions	attribute description
sta	1	c6	a6	1-6	station code
time	2	f8	f17.5	8-24	epoch time
arid	3	i4	i8	26-33	arrival id
jdate	4	i4	i8	35-42	julian date
stassid	5	i4	i8	44-51	stassoc id
chanid	6	i4	i8	53-60	instrument id
chan	7	c8	a8	62-69	channel code
iphase	8	c8	a8	71-78	reported phase
stype	9	c1	a1	80-80	signal type
deltim	10	f4	f6.3	82-87	delta time
azimuth	11	f4	f7.2	89-95	observed azimuth
delaz	12	f4	f7.2	97-103	delta azimuth
slow	13	f4	f7.2	105-111	observed slowness (s/deg)
delslo	14	f4	f7.2	113-119	delta slowness
ema	15	f4	f7.2	121-127	emergence angle
rect	16	f4	f7.3	129-135	rectilinearity
amp	17	f4	f10.1	137-146	amplitude, instrument corrected, nm
per	18	f4	f7.2	148-154	period
logat	19	f4	f7.2	156-162	log(amp/per)
clip	20	c1	a1	164-164	clipped flag
fm	21	c2	a2	166-167	first motion
snr	22	f4	f10.2	169-178	signal to noise ratio
qual	23	c1	a1	180-180	signal onset quality
auth	24	c15	a15	182-196	source/originator
commid	25	i4	i8	198-205	comment id
lddate	26	date	a17	207-223	load date

Relation:		**origin**			
Description:		Data on event location and confidence bounds			
attribute name	field no.	storage type	external format	character positions	attribute description
lat	1	f4	f9.4	1-9	estimated latitude
lon	2	f4	f9.4	11-19	estimated longitude
depth	3	f4	f9.4	21-29	estimated depth
time	4	f8	f17.5	31-47	epoch time
orid	5	i4	i8	49-56	origin id
evid	6	i4	i8	58-65	event id
jdate	7	i4	i8	67-74	julian date
nass	8	i4	i4	76-79	number of associated phases
ndef	9	i4	i4	81-84	number of locating phases
ndp	10	i4	i4	86-89	number of depth phases
grn	11	i4	i8	91-98	geographic region number
srn	12	i4	i8	100-107	seismic region number
etype	13	c7	a7	109-115	event type
depdp	14	f4	f9.4	117-125	estimated depth from depth phases
dtype	15	c1	a1	127-127	depth method used
mb	16	f4	f7.2	129-135	body wave magnitude
mbid	17	i4	i8	137-144	mb magid
ms	18	f4	f7.2	146-152	surface wave magnitude
msid	19	i4	i8	154-161	ms magid
ml	20	f4	f7.2	163-169	local magnitude
mlid	21	i4	i8	171-178	ml magid
algorithm	22	c15	a15	180-194	location algorithm used
auth	23	c15	a15	196-210	source/originator
commid	24	i4	i8	*212-219*	*comment id*
lddate	25	date	a17	221-237	load date

Relation:		wfdisc			
Description:		Waveform file header and descriptive information			
attribute name	field no.	storage type	external format	character positions	attribute description
sta	1	c6	a6	1-6	station
chan	2	c8	a8	8-15	channel
time	3	f8	f17.5	17-33	epoch time of first sample in file
wfid	4	i4	i8	35-42	waveform id
chanid	5	i4	i8	44-51	channel operation id
jdate	6	i4	i8	53-60	julian date
endtime	7	f8	f17.5	62-78	time+(nsamp-1)/samprate
nsamp	8	i4	i8	80-87	number of samples
samprate	9	f4	f11.7	89-99	sampling rate in samples/sec
calib	10	f4	f16.6	101-116	nominal calibration
calper	11	f4	f16.6	118-133	nominal calibration period
instype	12	c6	a6	135-140	instrument code
segtype	13	c1	a1	142-142	indexing method
datatype	14	c2	a2	144-145	numeric storage
clip	15	c1	a1	147-147	clipped flag
dir	16	c64	a64	149-212	directory
dfile	17	c32	a32	214-245	data file
foff	18	i4	i10	247-256	byte offset
commid	19	i4	i8	258-265	comment id
lddate	20	date	a17	267-283	load date